TTL advances using Aura

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551.510.5

EVIDENCE FOR A WORLD CIRCULATION PROVIDED BY THE MEASUREMENTS OF HELIUM AND WATER VAPOUR DISTRIBUTION IN THE STRATOSPHERE

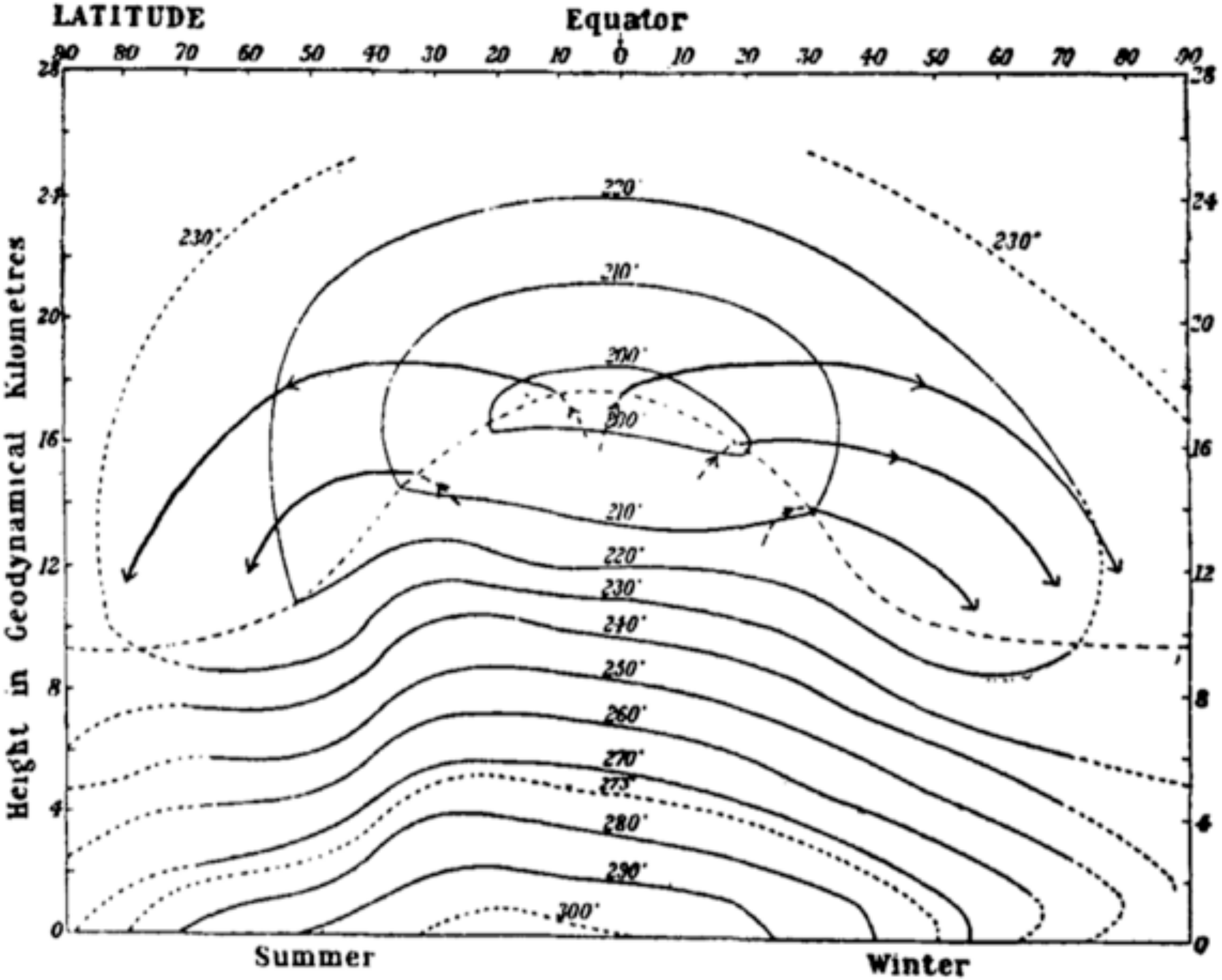
By A. W. BREWER, M.Sc., A.Inst.P.

(Manuscript received 23 February 1949)

1. Introduction

Between 1943 and 1945 the writer made some 16 ascents into the stratosphere over Southern England during which humidity measurements were made by means of a frost-point hygrometer. On

As regards the water content, all the ascents show that immediately above the tropopause there is a very rapid fall of frost-point, and above 1 km above the tropopause the air is very dry, with a frost-point of the order of 195°—200°A. The mean



Isotherms over the Globe

FIG. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.

In Situ Measurements of the Mixing Ratio of Water Vapor in the Stratosphere

DIETER KLEY, E. J. STONE[1], W. R. HENDERSON, J. W. DRUMMOND, W. J. HARROP,
A. L. SCHMELTEKOPF, T. L. THOMPSON AND R. H. WINKLER

NOAA, Aeronomy Laboratory, Boulder, CO 80303

(Manuscript received 26 April 1979, in final form 16 July 1979)

ABSTRACT

The results of four balloon flights of the NOAA ultraviolet fluorescence stratospheric water vapor instrument are presented. A series of improvements in the instrument has brought results which are credibly free from contamination by outgassing. The results are in essential agreement with the extensive soundings by H. J. Mastenbrook. The minimum water vapor mixing ratio occurs 2–3 km above the tropopause in both tropical and temperature latitudes. Our measured minimum values were 2.6 ppmv over Brazil (5°S) and 3.6 ppmv over Wyoming (41°N), with an estimated total error of 20%. This degree of dryness permits the conclusion that the global circulation originally proposed by Brewer is correct; i.e., that air enters the stratosphere from the troposphere in substantial quantities only through the tropical tropopause. This general circulation must apply to all other trace gases of tropospheric origin as well. The carbon monoxide measurements of Seiler support the conclusion.

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A Stratospheric Fountain?

REGINALD E. NEWELL AND SHARON GOULD-STEWART

Department of Meteorology and Physical Oceanography, Massachusetts Institute of Technology, Cambridge 02139

(Manuscript received 20 March 1981, in final form 28 July 1981)

ABSTRACT

A "stratospheric fountain", or area where air enters the stratosphere from the troposphere, is postulated based on an analysis of global 100 mb monthly mean temperatures. The temperature threshold is calculated from the observed global stratospheric water mixing ratio and fulfills the requirement of preserving low stratospheric humidity. The fountain occurs over the western tropical Pacific, northern Australia, Indonesia, and Malaysia in the November–March period and over the Bay of Bengal and India during the Monsoon. It is suggested that the major portion of the stratospheric air supply enters through these areas with most of the exchange occurring in the November–March period. Methods are proposed for substantiating the existence of the stratospheric fountain.

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Q. J. R. Meteorol. Soc. (1998), **124**, pp. 1579–1604

The tropical tropopause

By E. J. HIGHWOOD* and B. J. HOSKINS
University of Reading, UK

(Received 23 May 1997; revised 7 January 1998)

SUMMARY

The physical meaning of several different tropical tropopause definitions is examined using atmospheric data from a variety of sources, and model output. The conventional lapse-rate definition of the tropopause appears to have little physical relevance in the tropics, although it is easy to use operationally. A four year 'climatology' of the tropical tropopause from the European Centre for Medium-Range Weather Forecasts (ECMWF) analyses is presented. The zonal mean picture shows the annual cycle in properties that has been related to the extratropical stratospheric wave pump. However, there are large and important zonal asymmetries. These include a relatively low pressure and temperature at the tropopause near the west Pacific heating region during December–January–February, and a striking region with low pressure on the tropopause over India during June–July–August. Results from a baroclinic model with imposed diabatic heating are used to support the hypothesis that both these features can be attributed to the direct response of the atmosphere to a large-scale region of tropospheric diabatic heating. It is proposed that the stratospheric pump provides the general picture for the upper troposphere/lower stratosphere region, but that tropospheric convection is crucial in determining the important zonal asymmetries in this region.

KEYWORDS: Tropical convection Stratospheric pump Stratospheric water vapour

Q. J. R. Meteorol. Soc. (1998), **124**, pp. 1579–1604

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can be attributed to th
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region, but that tropo

KEYWORDS:

On the temperature structure of the tropical substratosphere

John Thuburn
Department of Meteorology, University of Reading, Reading, United Kingdom

George C. Craig
Joint Centre for Mesoscale Meteorology, Department of Meteorology, University of Reading, Reading, United Kingdom

Received 3 February 2001; revised 19 July 2001; accepted 25 July 2001; published 29 January 2002.

[1] The region of the tropical atmosphere between the main convective outflow level around 200–150 hPa and the cold point, the substratosphere, shares properties of the troposphere and the stratosphere. An analogous region exists in single-column radiative-convective models between the top of the convectively adjusted region and the cold point, so a radiative-convective model has been used to investigate the radiative and dynamical factors that allow a substratosphere to exist and to which it is sensitive. A key result is that localized heating in the 15 μm CO_2 band, owing to the sharp curvature in the temperature profile near the convection top, forces apart the cold point and convection top creating the substratosphere. A possible radiation-convective-transport feedback involving O_3 is identified that could amplify the response of the substratosphere and cold point to changes in forcing such as sea surface temperature or stratospheric meridional circulation. A comparison of timescales suggests that the substratosphere is characterized by (1) a radiative timescale shorter than the convective timescale, so that radiation dominates in setting the temperature structure, but (2) a convective transport timescale shorter than the timescales for other processes affecting O_3, so that the import of air from the boundary layer keeps O_3 mixing ratios low there. *INDEX TERMS:* 0300 Atmospheric Composition and Structure, 3359 Meteorology and Atmospheric Dynamics: Radiative processes, 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions, 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology

A barrier to vertical mixing at 14 km in the tropics: Evidence from ozonesondes and aircraft measurements

Ian Folkins,[1] Max Loewenstein,[2] Jim Podolske,[2] Samuel J. Oltmans,[3] Michael Proffitt[4]

Abstract. We use ozonesondes launched from Samoa (14°S) during the Pacific Exploratory Mission (PEM) Tropics A to show that O_3 mixing ratios usually start increasing toward stratospheric values near 14 km. This is well below the tropical tropopause (as defined either in terms of lapse rate or cold point), which usually occurs between 16 and 17 km. We argue that the main reason for this discrepancy in height between the chemopause and tropopause is that there is very little convective detrainment of ozone-depleted marine boundary layer air above 14 km. We conjecture that the top of the Hadley circulation occurs at roughly 14 km, that convective penetration above this altitude is rare, and that air that is injected above this height subsequently participates in a slow vertical ascent into the stratosphere. The observed dependence of ozone on potential temperature in the transitional zone between the 14-km chemopause and the tropical tropopause is consistent with what would be expected from this hypothesis given calculated clear-sky heating rates and typical in situ ozone production rates in this region. An observed anticorrelation between ozone and equivalent potential temperature below 14 km is consistent with what would be expected from an overturning Hadley circulation, with some transport of high O_3/low θ_e air from midlatitudes. We also argue that the positive correlations between O_3 and N_2O in the transitional zone obtained during the 1994 Airborne Southern Hemisphere Ozone Experiment/Measurements for Assessing the Effects of Stratospheric Aircraft) (ASHOE/MAESA) campaign support the notion that air in this region does have trace elements of stratospheric air (as conjectured previously), so that some of the ozone in the transitional zone does originate from the stratosphere rather than being entirely produced in situ.

GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 16, PAGES 2513-2516, AUGUST 15, 2000

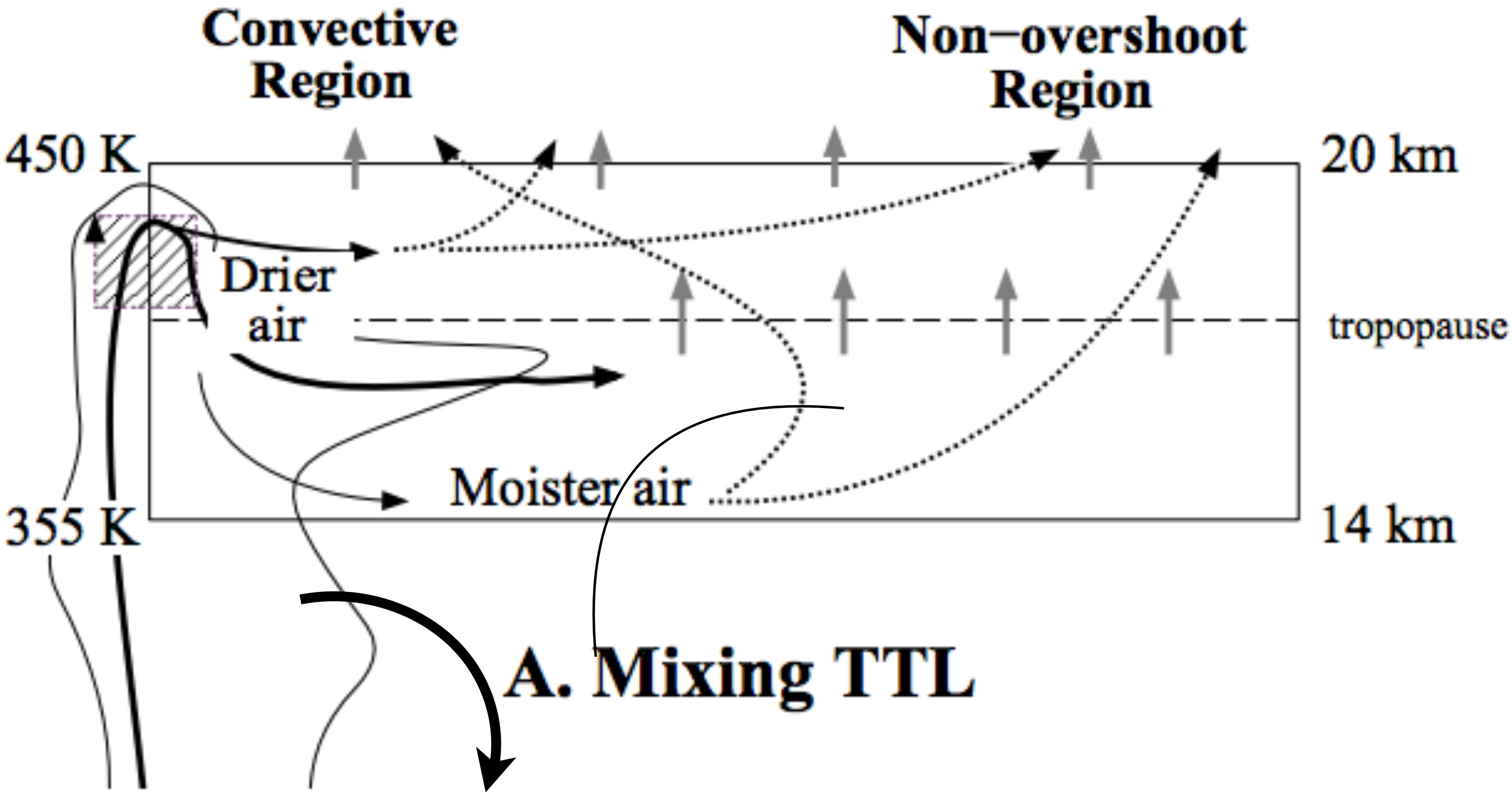
On the control of stratospheric humidity

Steven C. Sherwood
Universities Space Research Association, Seabrook, MD

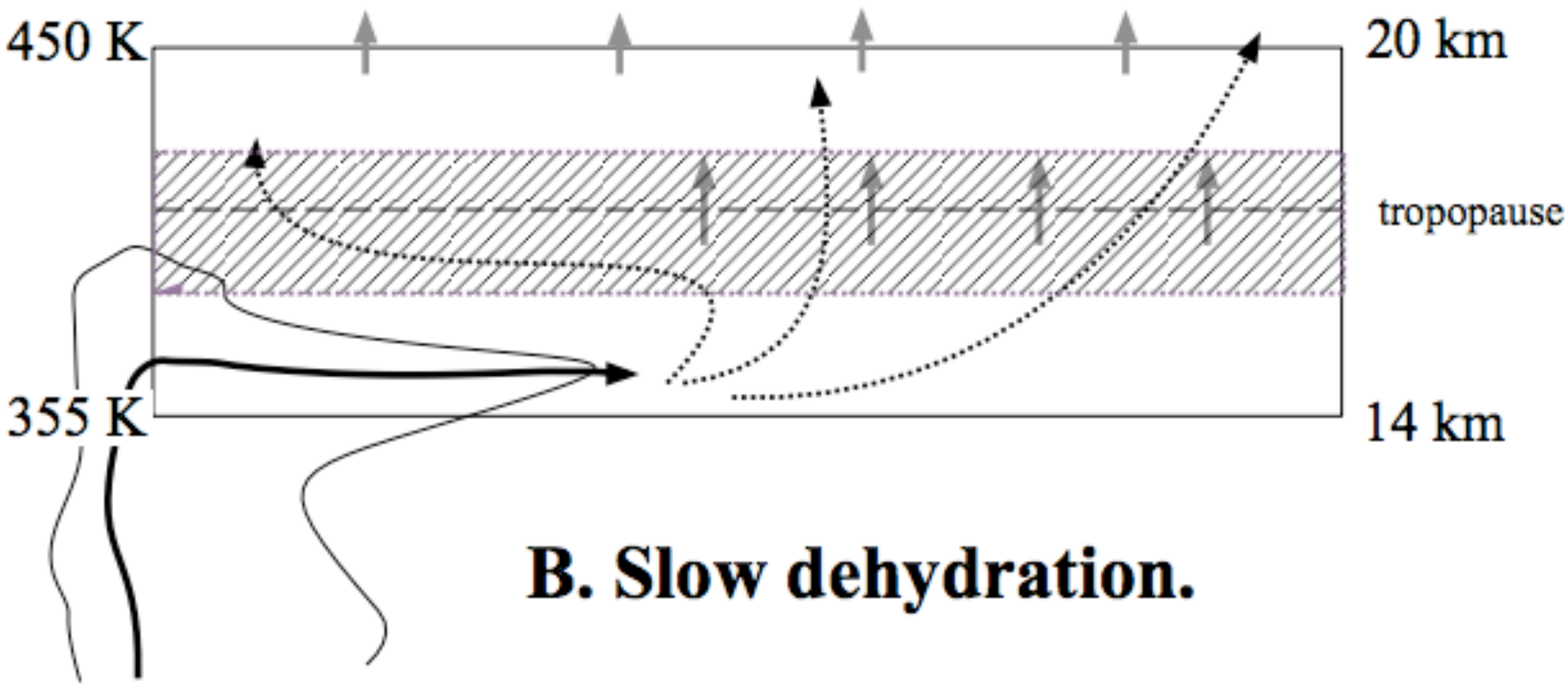
Andrew E. Dessler
Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD

The Mixing Layer Hypothesis

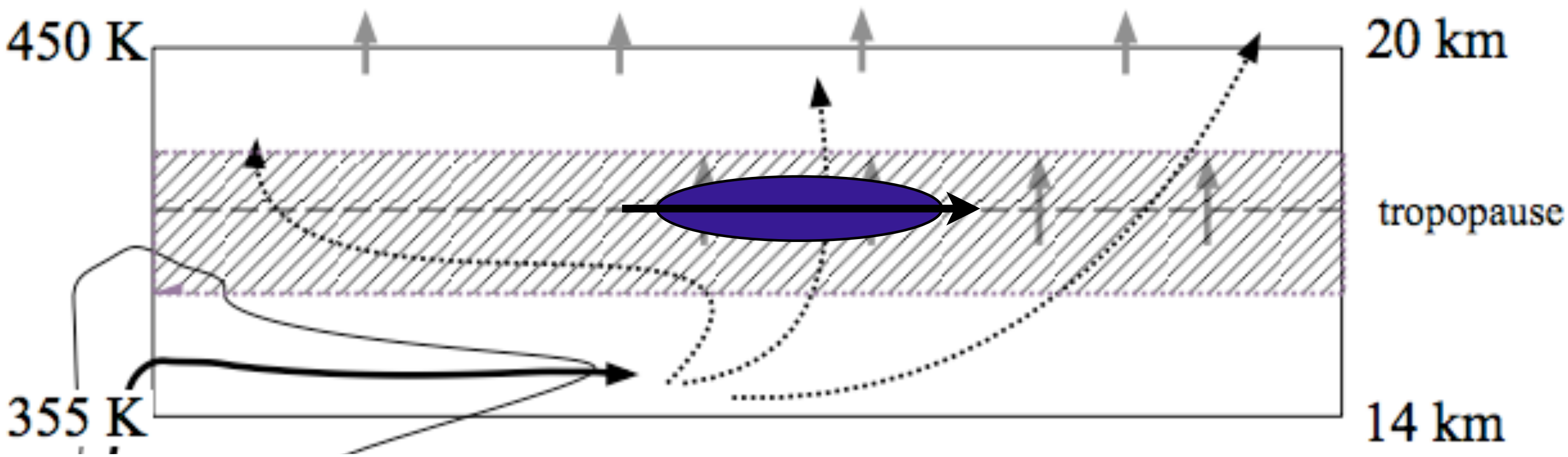
Our proposal focuses on a region that we will hereafter refer to as the tropical tropopause layer (TTL), that region of the tropical atmosphere extending from the zero net radiative heating level (355 K, 150 hPa, 14 km) to the highest level that convection reaches (~420-450 K, 70 hPa, 18-20 km). The TTL can be thought of as a transition layer between the troposphere and stratosphere. There is strong


Convective Region
Non−overshoot Region
450 K
20 km
Drier air
tropopause
Moister air
355 K
14 km

A. Mixing TTL



B. Slow dehydration.



GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 14, PAGES 2799-2802, JULY 15, 2001

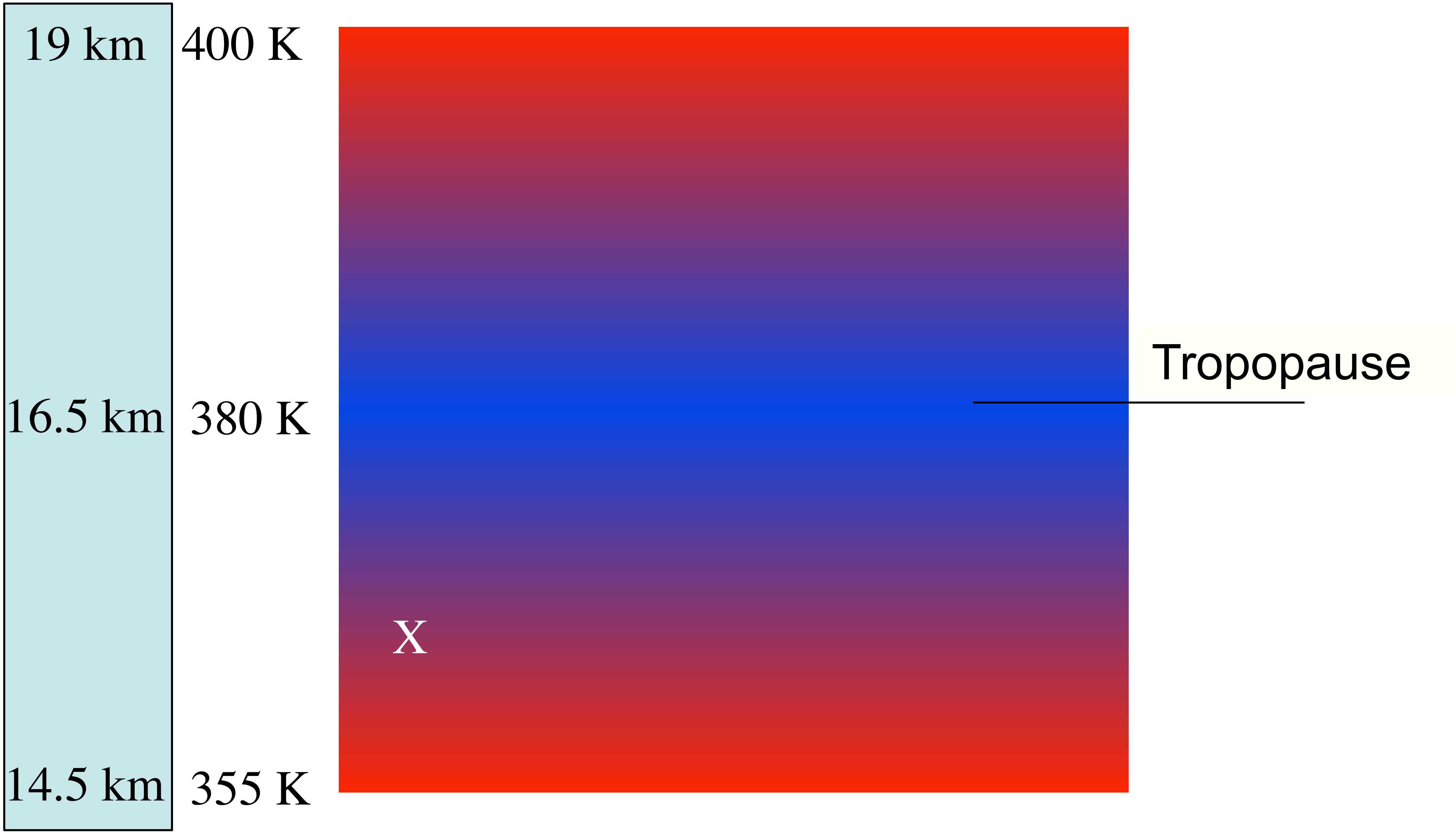
Horizontal transport and the dehydration of the stratosphere

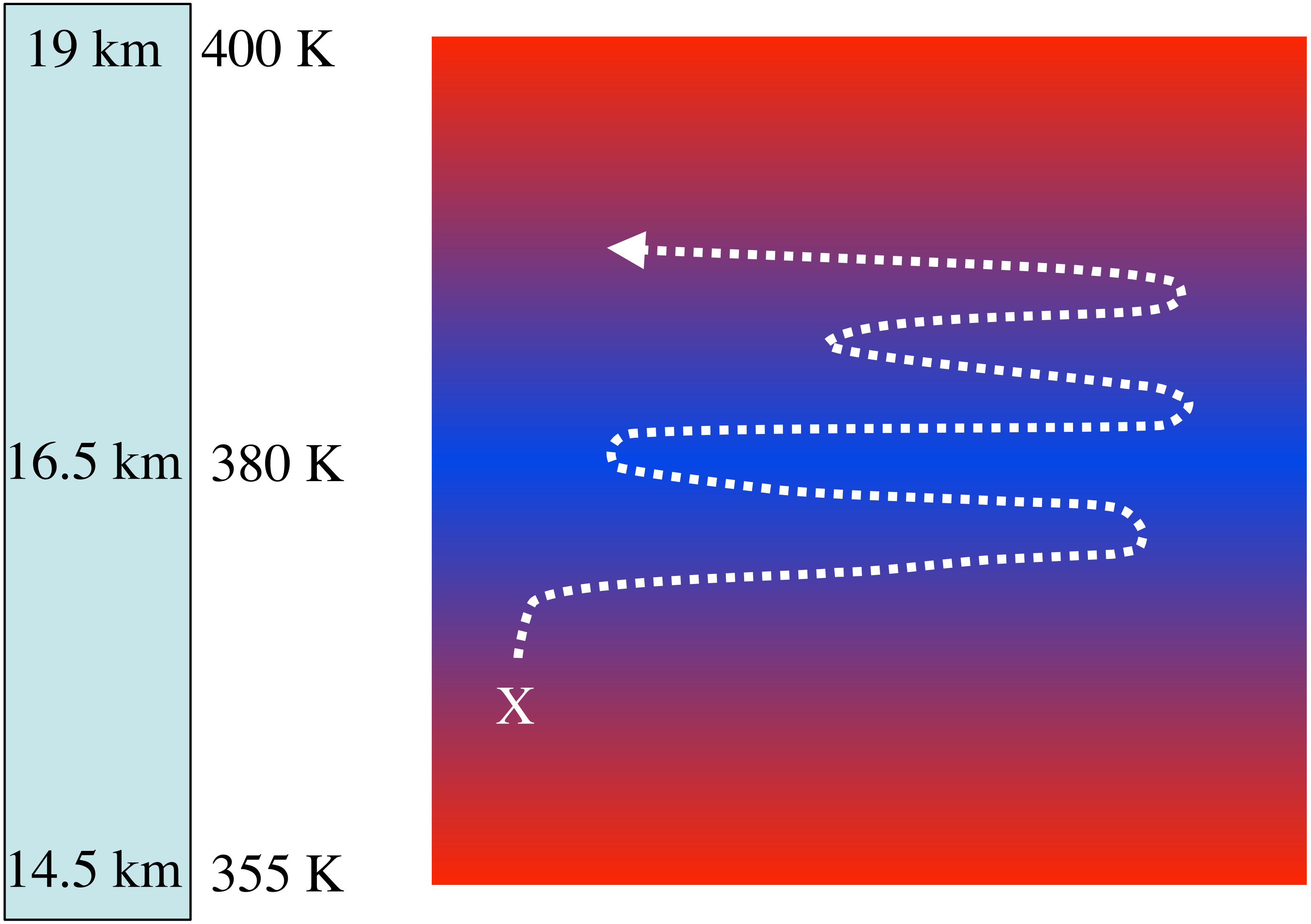
James R. Holton

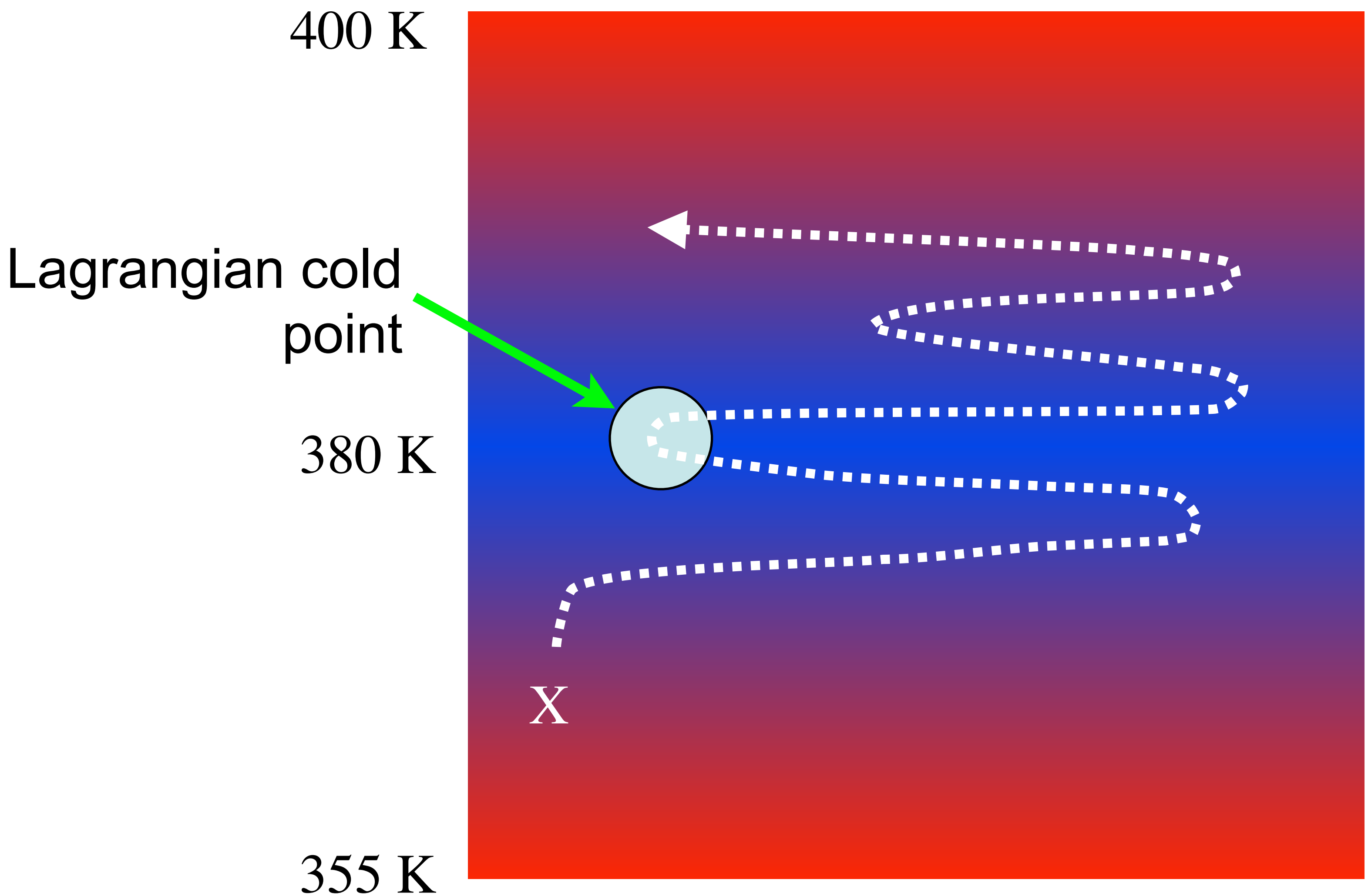
University of Washington, Seattle, Washington

Andrew Gettelman

National Center for Atmospheric Research, Boulder, Colorado


19 km
400 K
16.5 km
380 K
14.5 km
355 K
Tropopause
X


19 km
400 K
16.5 km
380 K
14.5 km
355 K
X


400 K
Lagrangian cold point
380 K
X
355 K

TTL review

- understanding the annual and interannual variations in H_2O
- trends in H_2O?
- other constituents

TTL review

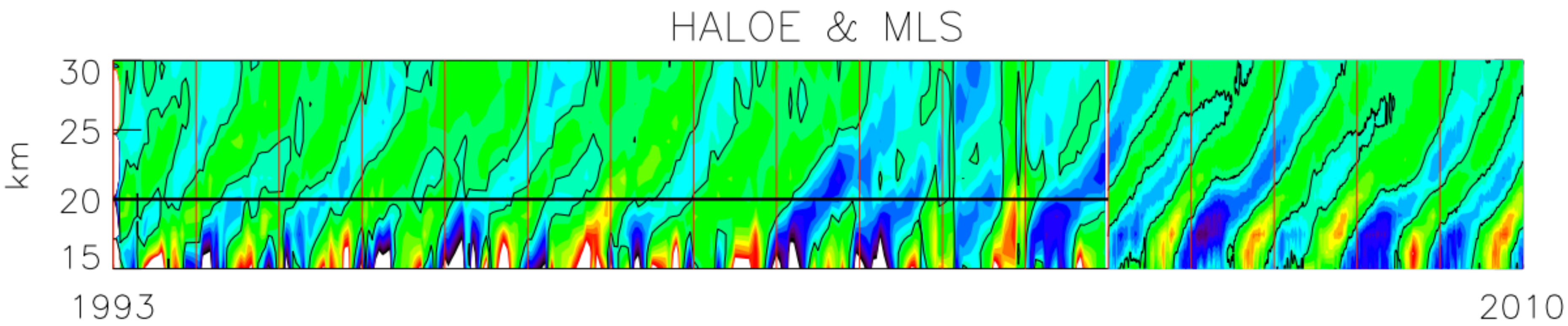
- understanding the annual and interannual variations in H_2O
- trends in H_2O?
- other constituents

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. D2, PAGES 3989–4006, FEBRUARY 20, 1996

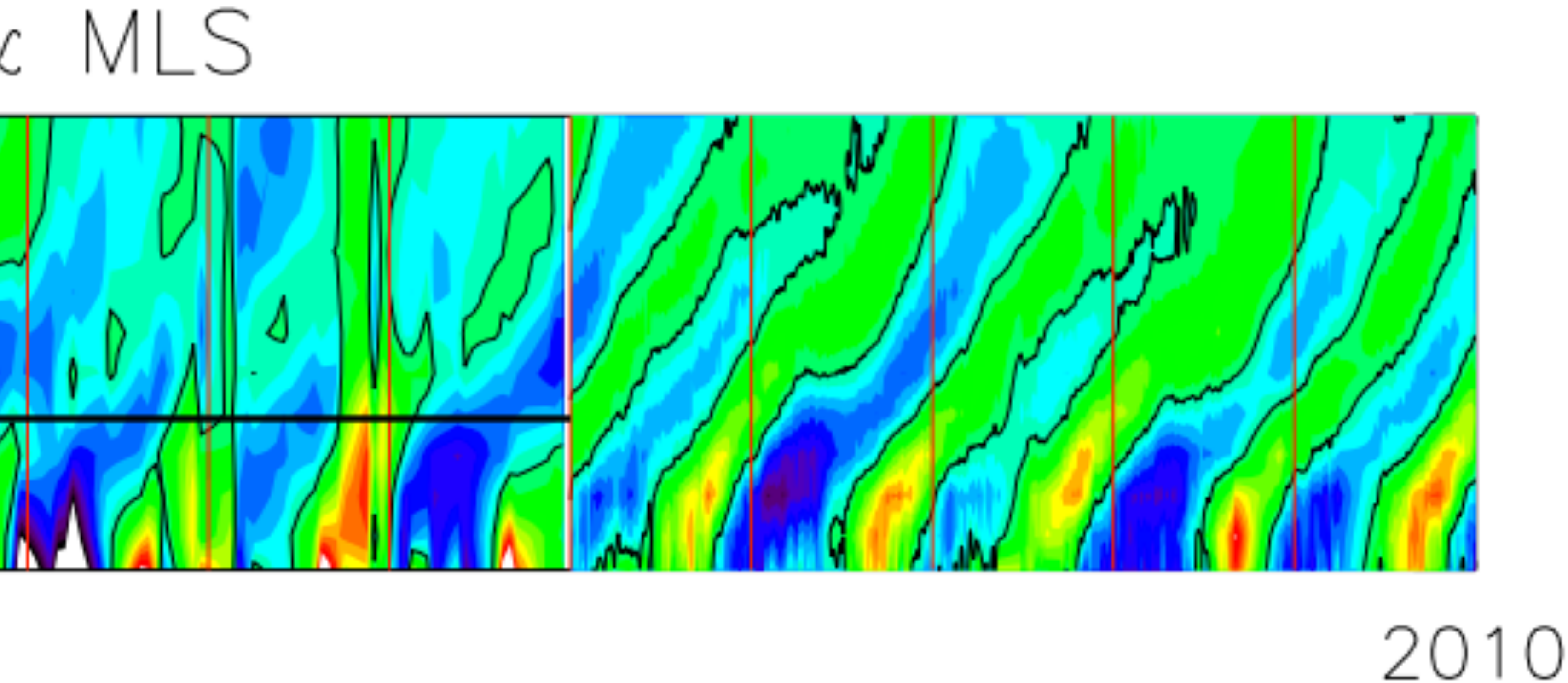
An atmospheric tape recorder: The imprint of tropical tropopause temperatures on stratospheric water vapor

Philip W. Mote,[1,2] Karen H. Rosenlof,[3,4] Michael E. McIntyre,[5]
Ewan S. Carr,[1,6] John C. Gille,[7] James R. Holton,[8] Jonathan S. Kinnersley,[1,9]
Hugh C. Pumphrey,[1] James M. Russell III,[10] and Joe W. Waters[11]

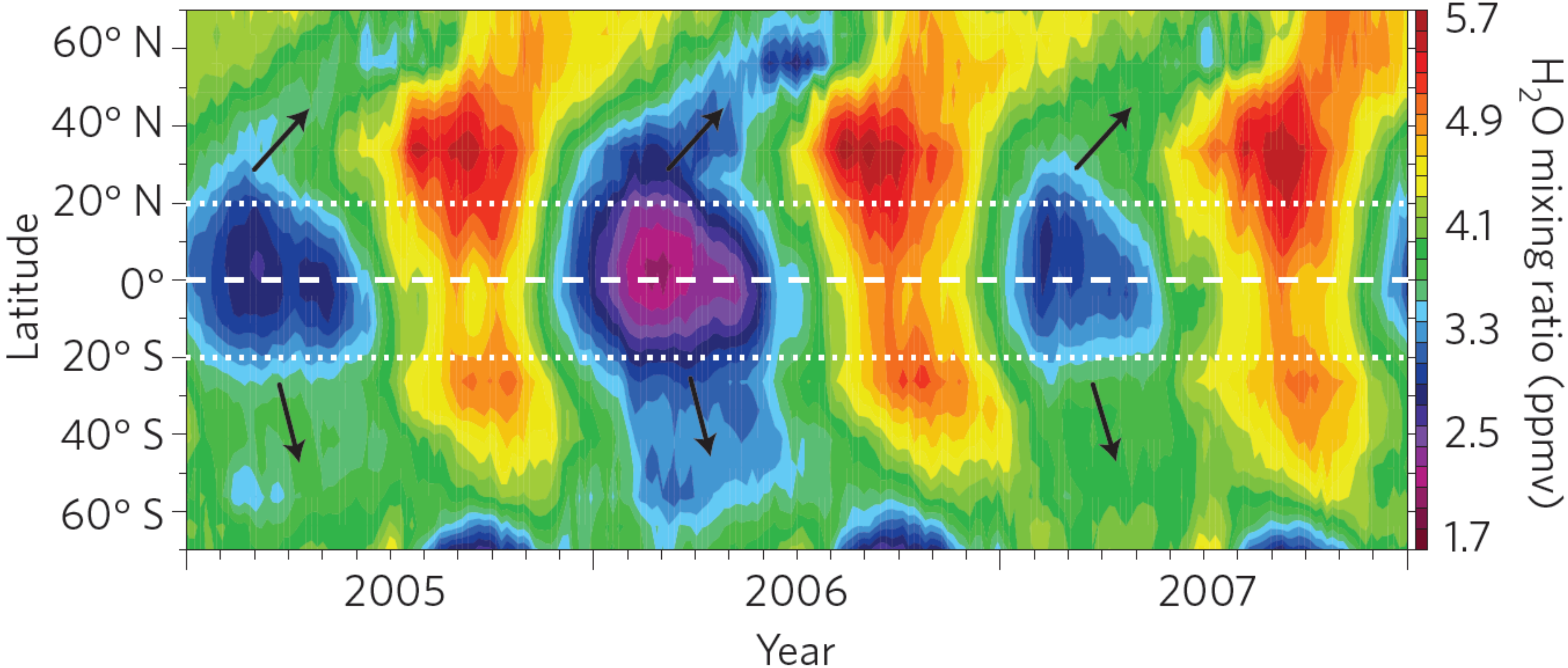
Abstract. We describe observations of tropical stratospheric water vapor q that show clear evidence of large-scale upward advection of the signal from annual fluctuations in the effective "entry mixing ratio" q_E of air entering the tropical stratosphere. In other words, air is "marked," on emergence above the highest cloud tops, like a signal recorded on an upward moving magnetic tape. We define q_E as the mean water vapor mixing ratio, at the tropical tropopause, of air that will subsequently rise and enter the stratospheric "overworld" at about 400 K. The observations show a systematic phase lag, increasing with altitude, between the annual cycle in q_E and the annual cycle in q at higher altitudes. The



Schoeberl et al., ACP, 2012



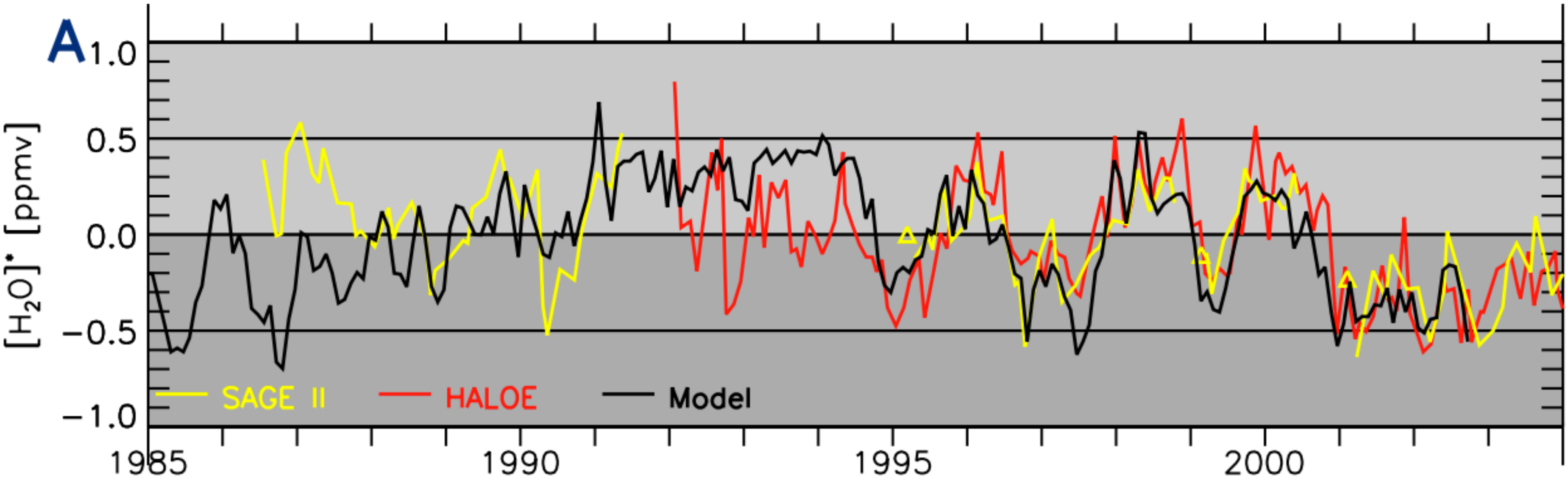
Schoeberl et al., ACP, 2012



Aura MLS data @ 390 K

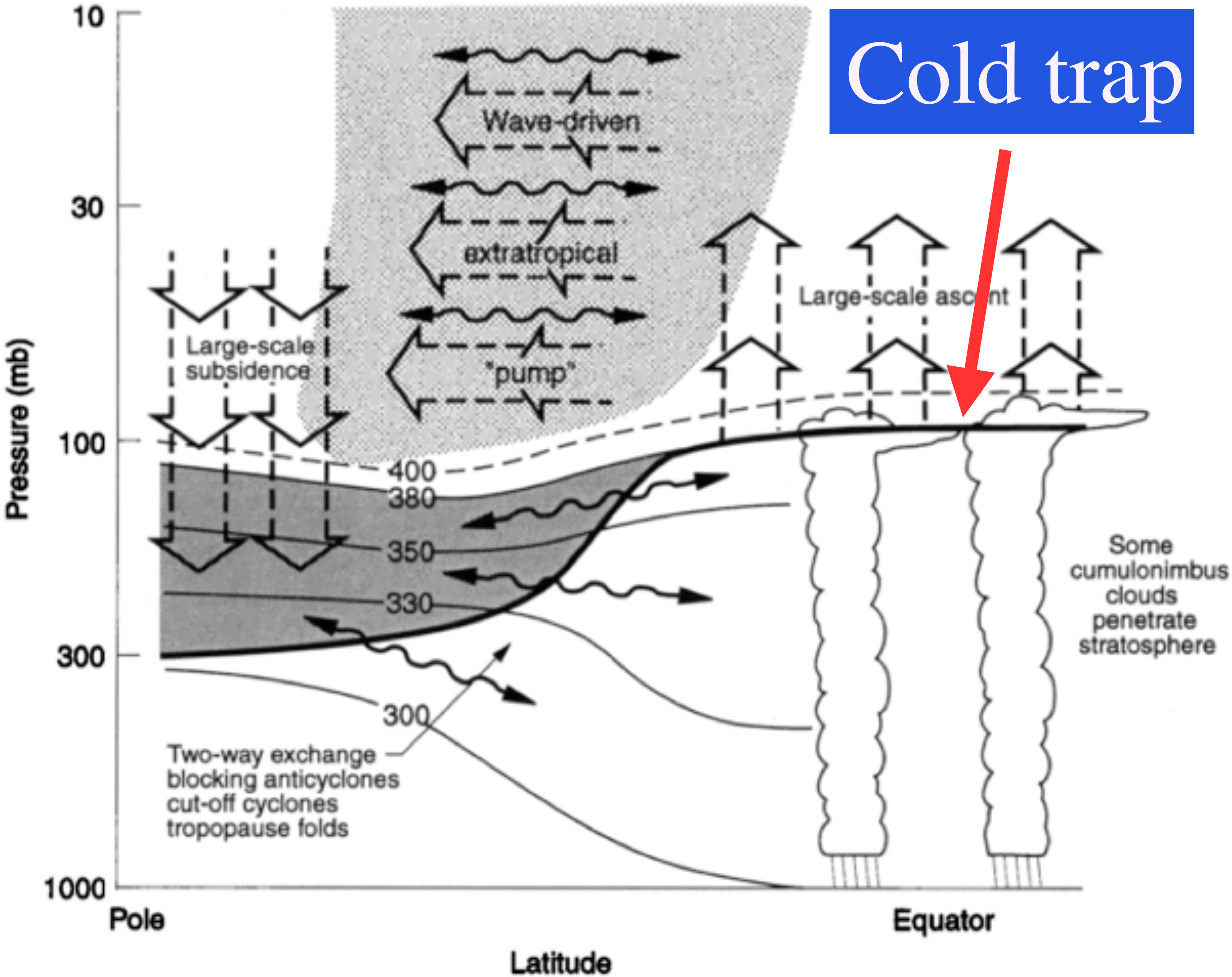
“sideways taperecorder”

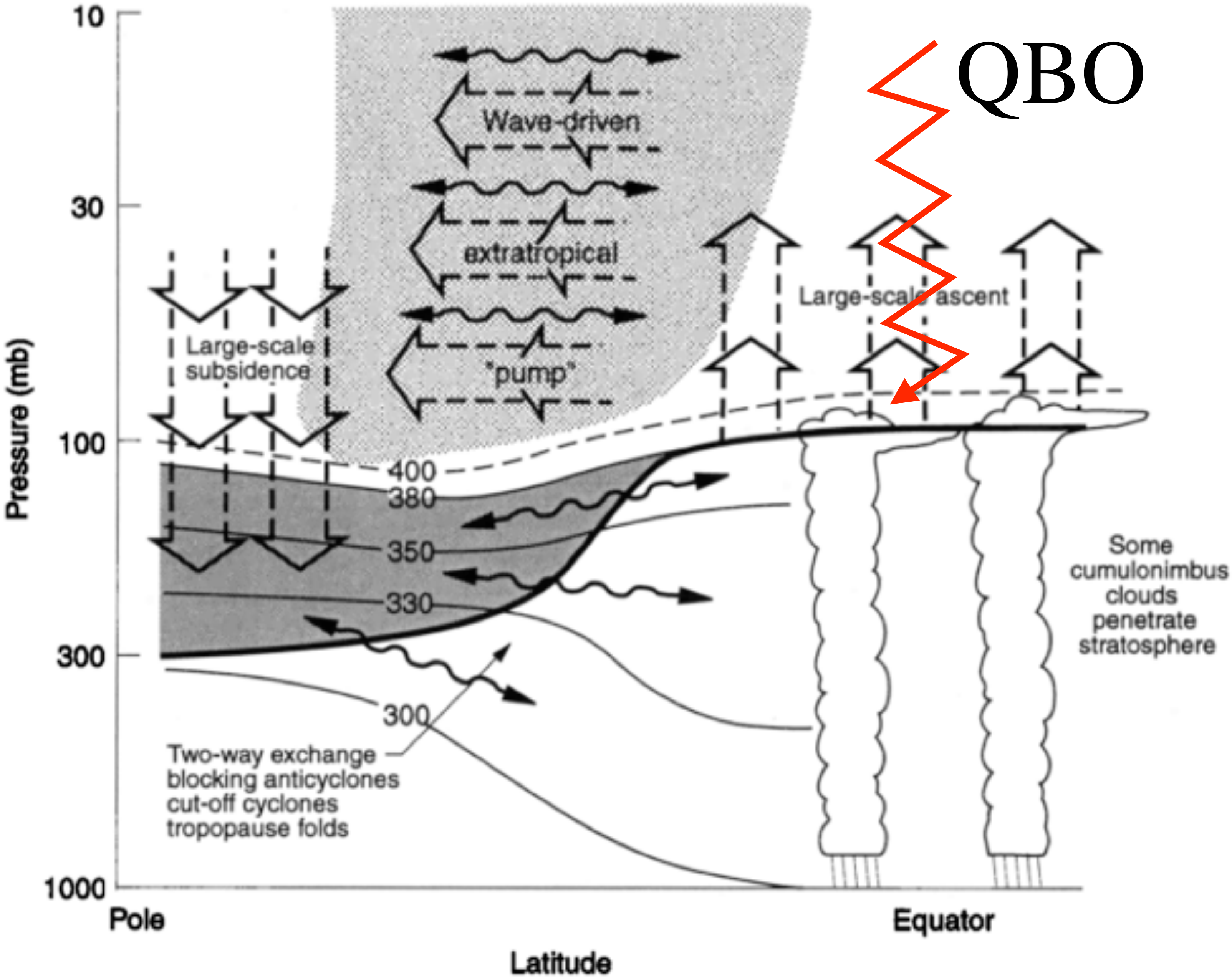
Randel and Jensen, Nature Geosci., 2013



Fueglistaler and Haynes, JGR, 2005

updated in Fueglistaler et al., JGR, 2013


Cold trap
Wave-driven
extratropical
"pump"
Large-scale subsidence
Large-scale ascent
Some cumulonimbus clouds penetrate stratosphere
Two-way exchange
blocking anticyclones
cut-off cyclones
tropopause folds
400
380
350
330
300
10
30
100
300
1000
Pressure (mb)
Pole
Equator
Latitude



QBO
10
30
100
300
1000
Pressure (mb)
Wave-driven
extratropical
"pump"
Large-scale subsidence
Large-scale ascent
400
380
350
330
300
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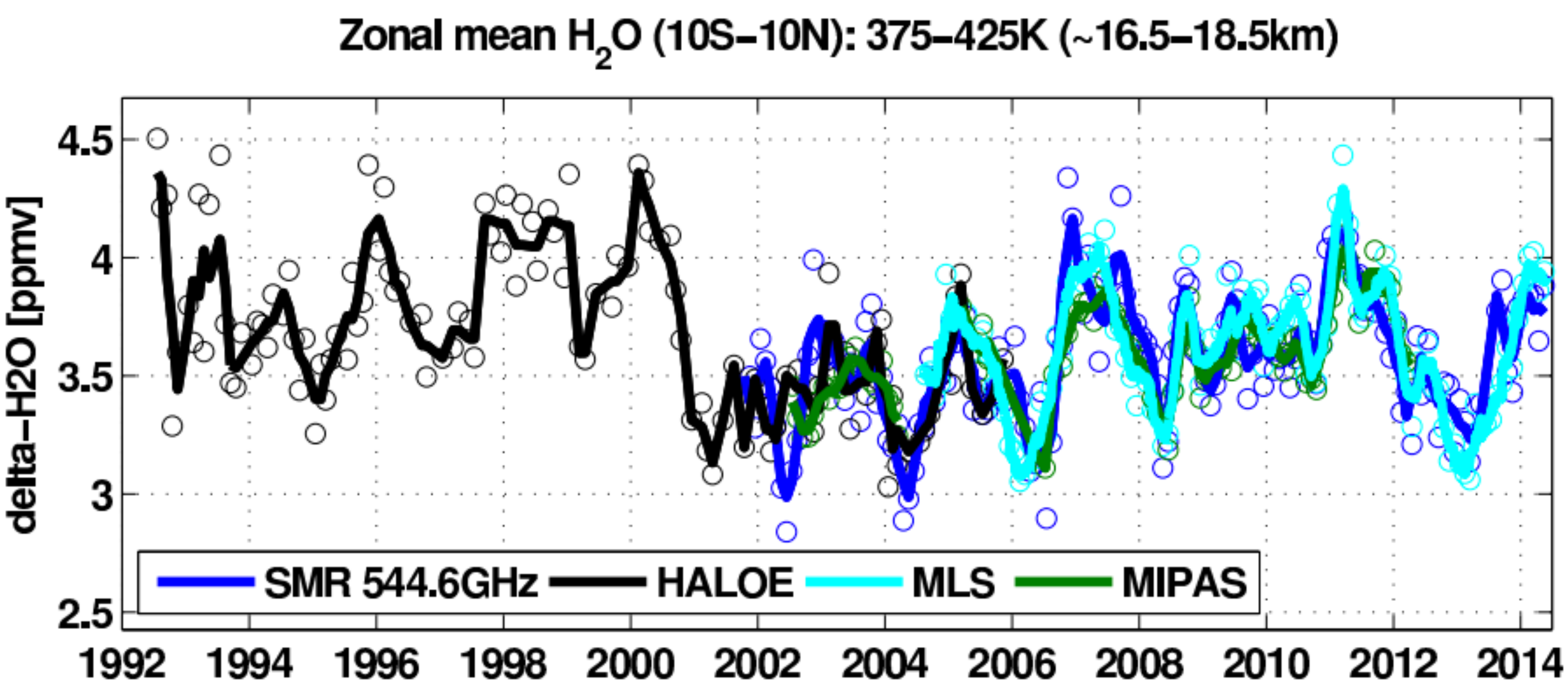
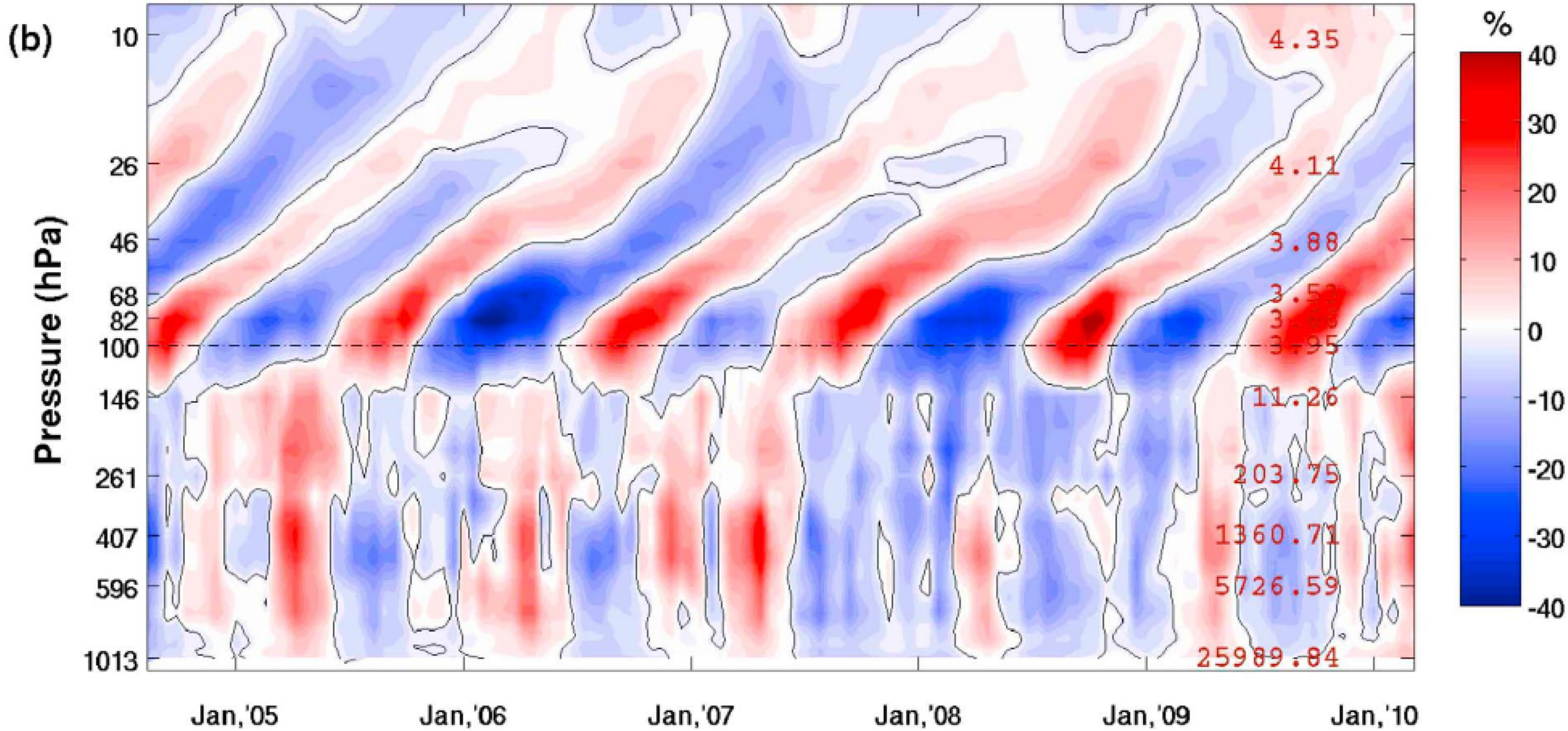
tropopause folds
Pole
Equator
Latitude

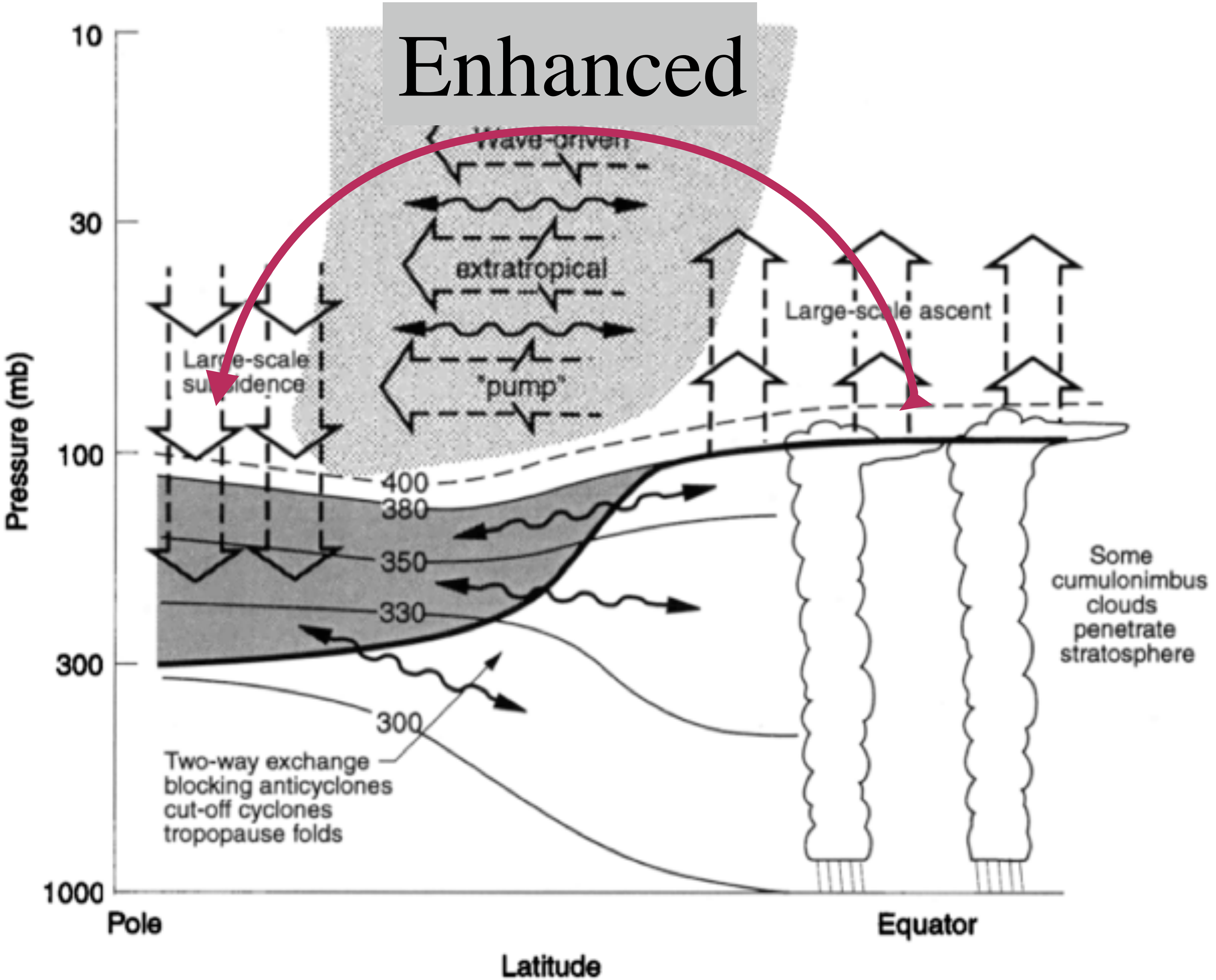
Giorgetta and Bengtsson, JGR, 1999; Randel and Gaffen, JGR, 2000; Geller et al, JAS, 2002



J. Urban, S. Lossow, G. Stiller, and W. Read, EOS, 2014



% change in H_2O mixing ratio from combined MLS + AIRS data set
Liang et al., JGR, 2011


Enhanced
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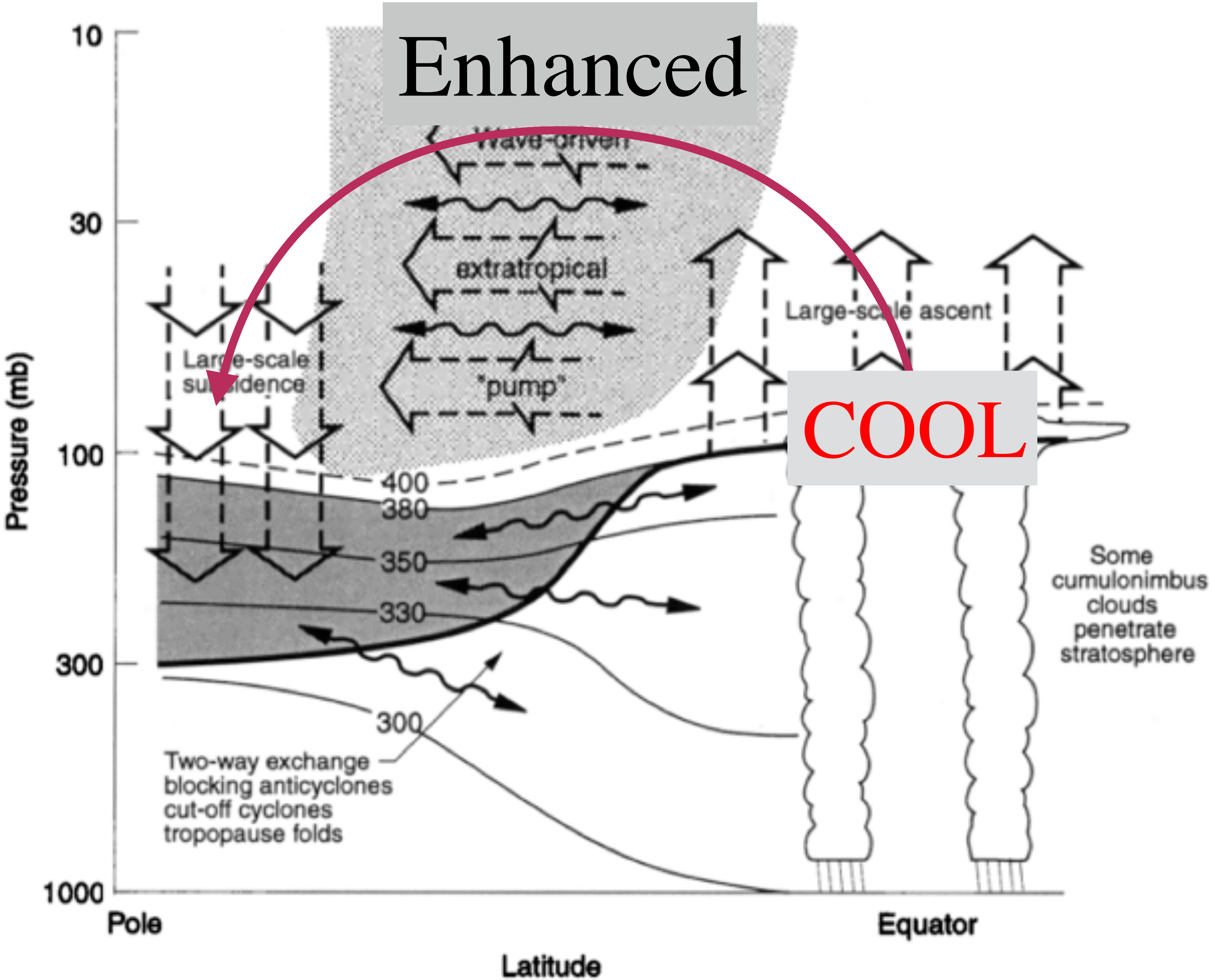
Enhanced
COOL
Wave-driven
extratropical
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Large-scale ascent
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350
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Eos, Vol. 95, No. 27, 8 July 2014

EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 95 NUMBER 27

8 July 2014

PAGES 245–252

Another Drop in Water Vapor

PAGES 245–246

In 2000 a sudden severe drop in stratospheric water vapor levels interrupted the supposed long-term increase of this greenhouse gas, an important contributor to global warming and climate variability. Satellite sensors observed a recovery in the following years, hidden behind a large variability. More recently, during 2011 and 2012, measurements

[*Dessler et al.*, 2013]. In addition, climate models uniformly predict that stratospheric water vapor concentrations will continue to increase in the future [e.g., *Gettelman et al.*, 2009].

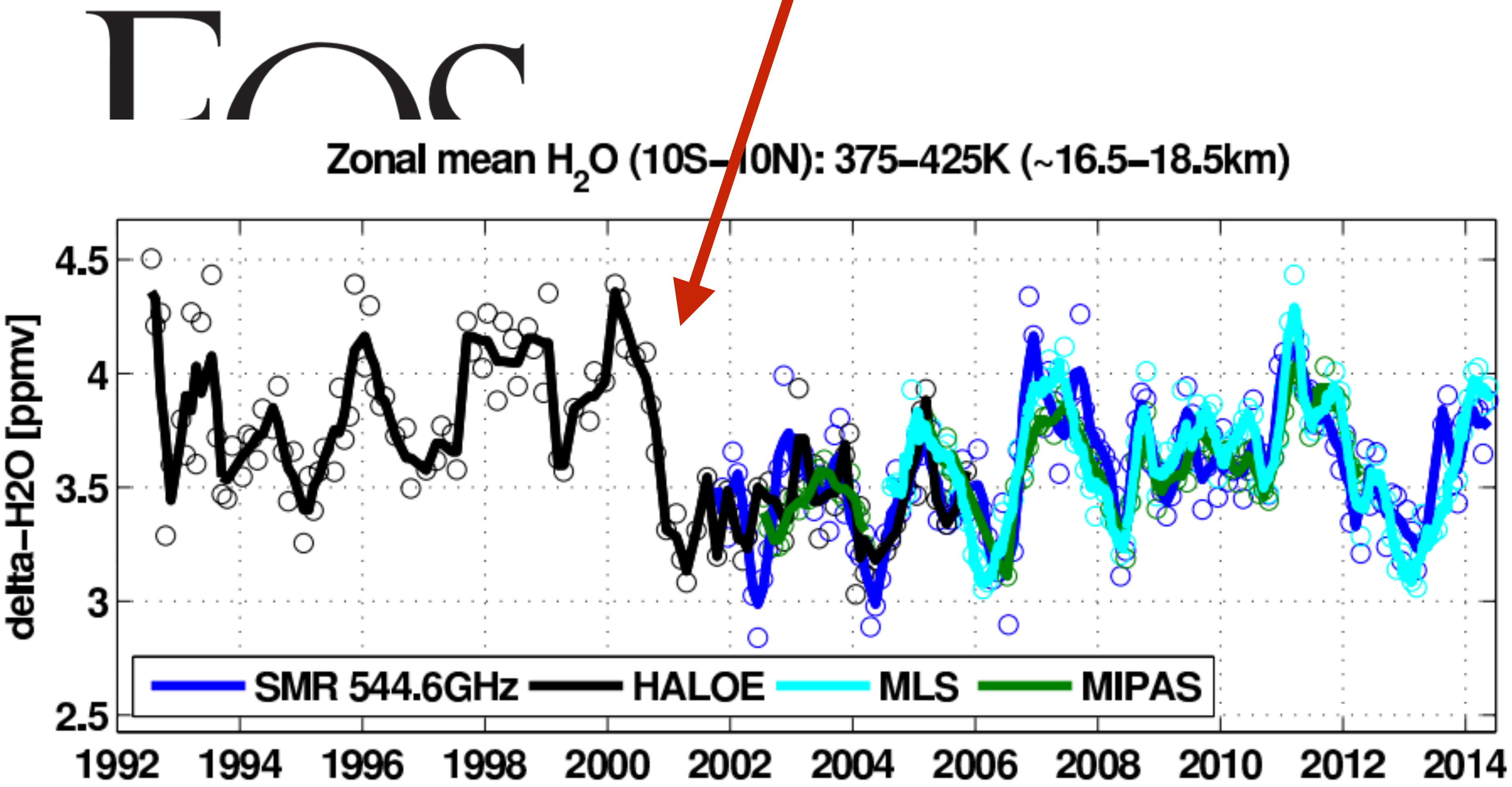
Sudden Drops in Water Vapor

In 2000 a severe drop in stratospheric water vapor levels interrupted the supposed long-

temperature) determines how much water vapor continues on its upward path into the stratosphere and how much is removed by a freeze-drying process. The other is the oxidation of methane, which is the only important chemical source of water vapor in the stratosphere. The increase in stratospheric water vapor concentrations during the past century cannot fully be explained by changing tropopause temperatures—cold point temperatures decreased while water vapor overall increased—or increasing levels of the greenhouse gas methane. Observed methane

J. Urban, S. Lossow, G. Stiller, and W. Read, EOS, 2014

Randel et al., JGR, 2006; Dhomse et al, ACP 2008



J. Urban, S. Lossow, G. Stiller, and W. Read, EOS, 2014

Randel et al., JGR, 2006; Dhomse et al, ACP 2008

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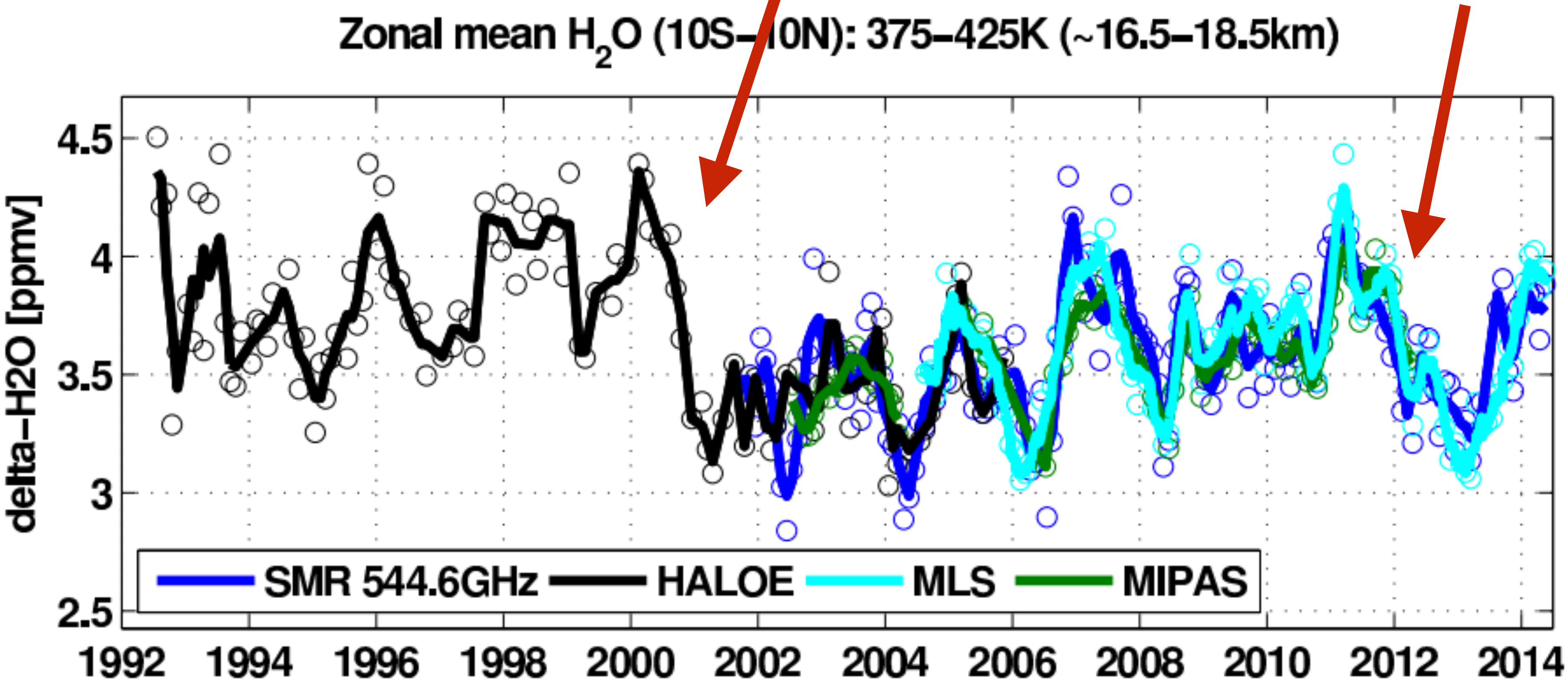
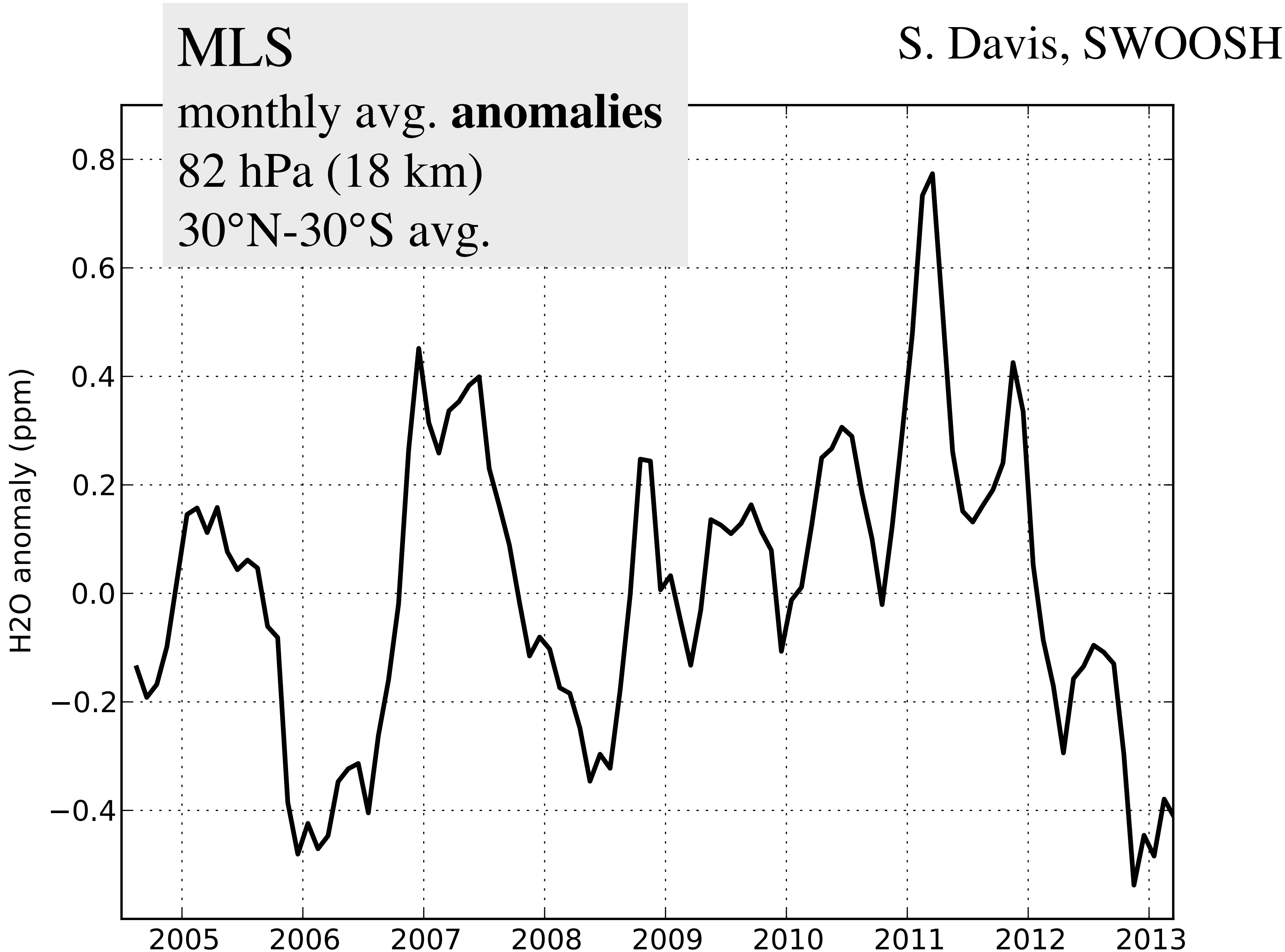
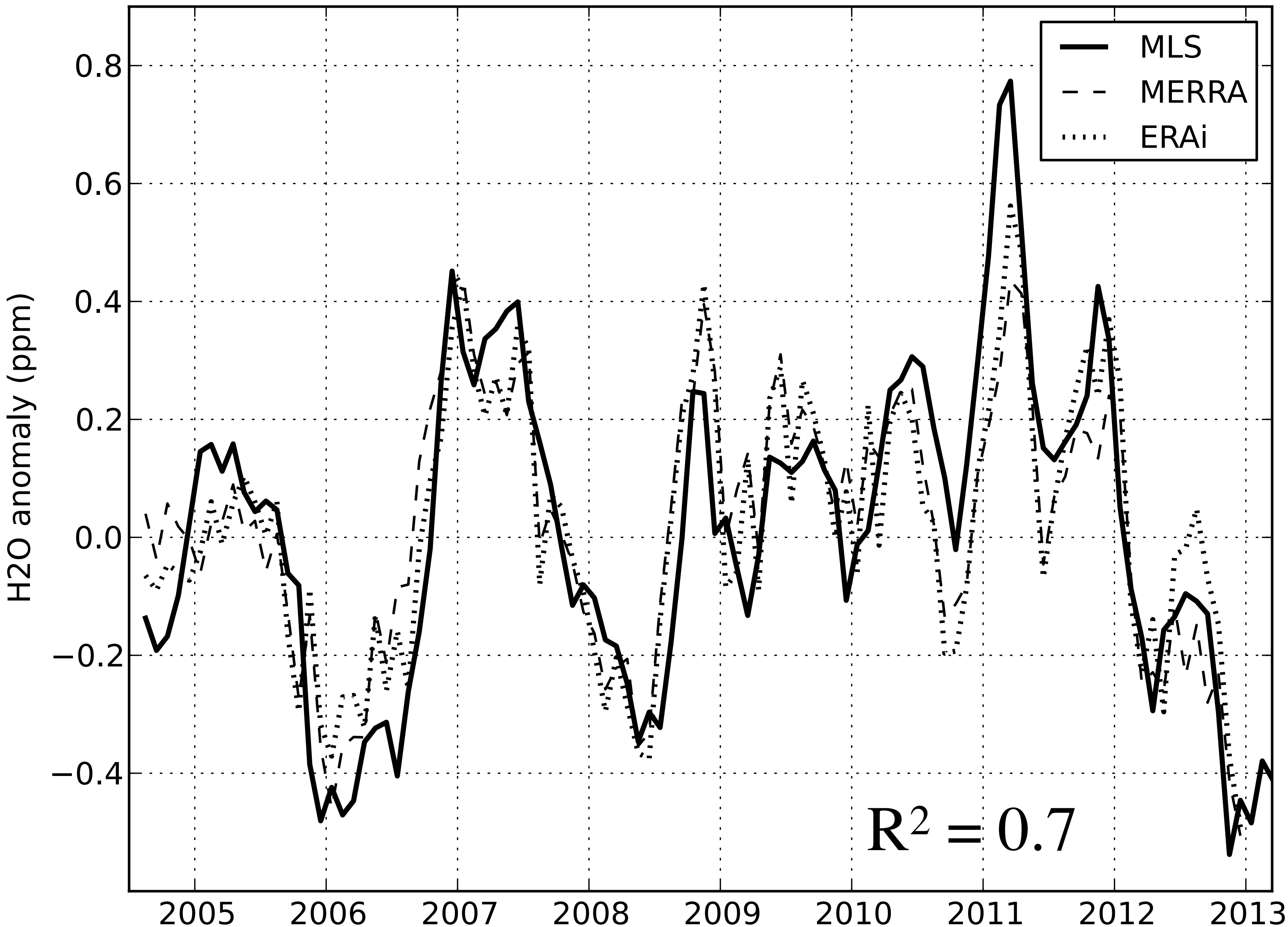


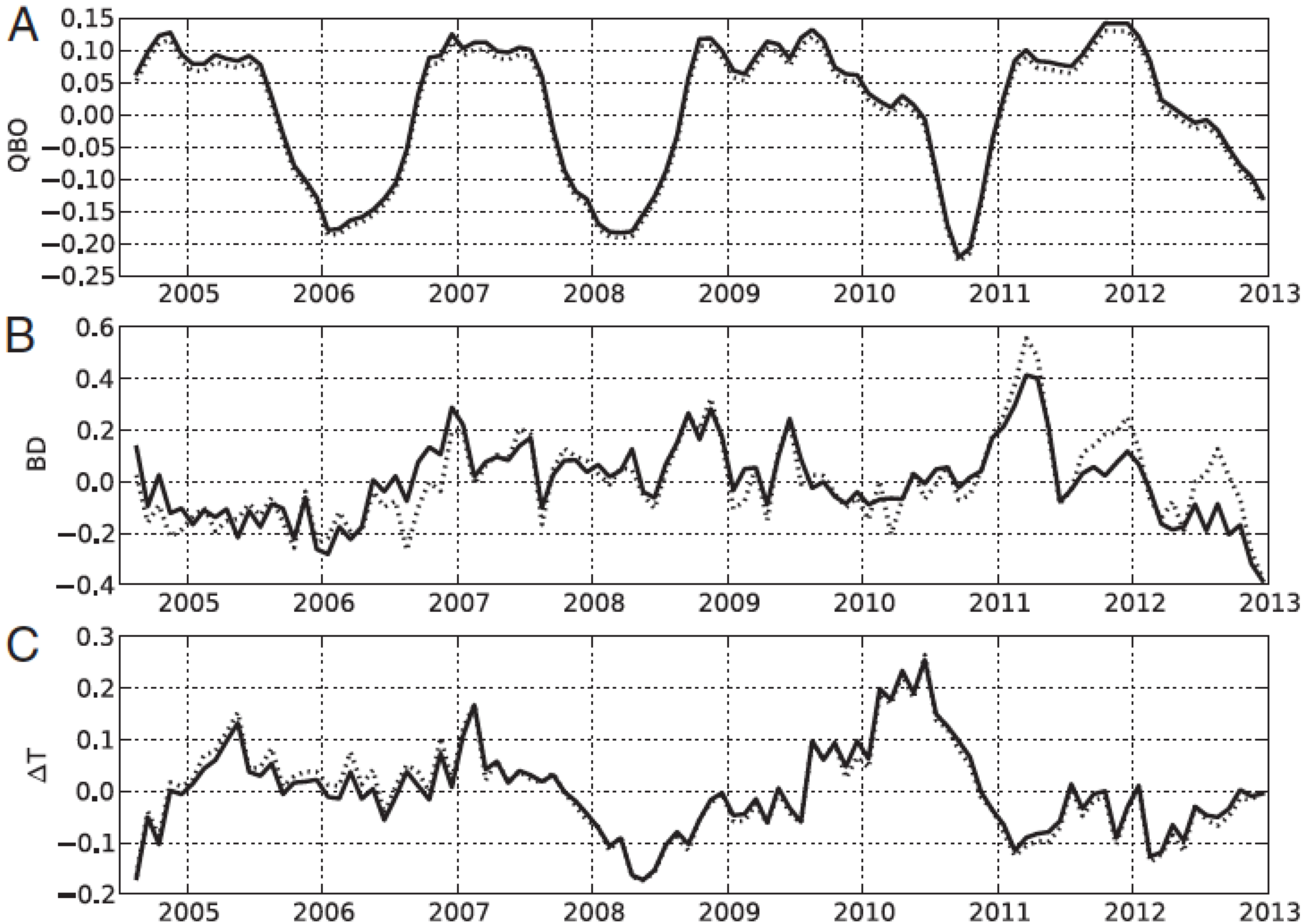
J. Urban, S. Lossow, G. Stiller, and W. Read, EOS, 2014


MLS
monthly avg. **anomalies**
82 hPa (18 km)
30°N-30°S avg.
S. Davis, SWOOSH
H2O anomaly (ppm)
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
2005
2006
2007
2008
2009
2010
2011
2012
2013

- <u>Multivariate linear least-squares fit:</u>
- $H2O^* = a\,QBO + b\,BD + c\,\Delta T + r$
- QBO = QBO index (NOAA CPC)
- BD = tropical avg. 82-hPa heating rate anomaly
- ΔT = 500-hPa tropical avg. temperature anomaly
- BD & ΔT come from MERRA and ERAi
- r = residual



Dessler et al., PNAS, 2013



Dessler et al, PNAS, 2013

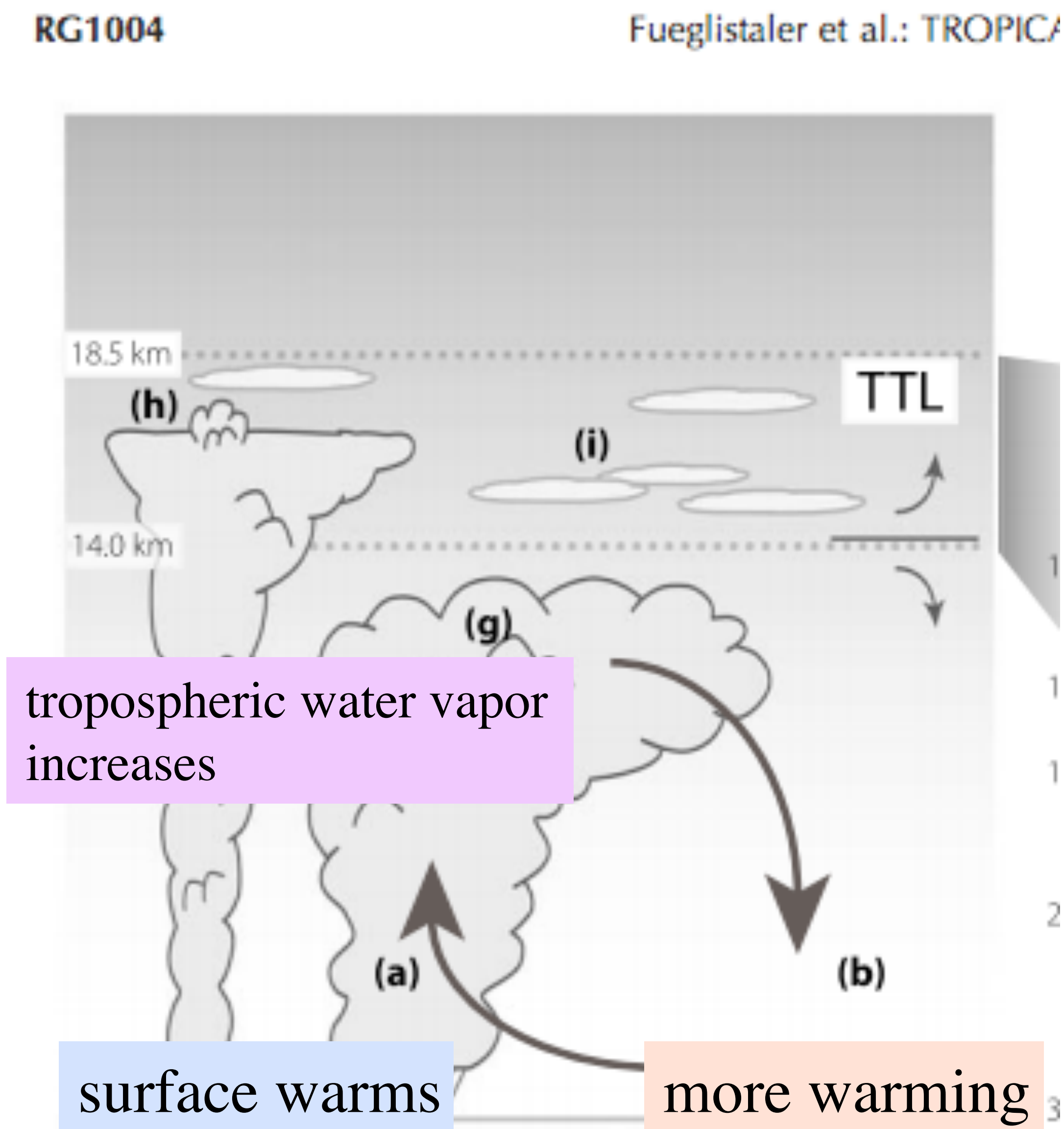
Table 1. Coefficients from regressions of the $H_2O_{ov\text{-}entry}$ time series

	MLS observations	
Regressor	MERRA	ERAi
QBO	0.09 ± 0.05	0.09 ± 0.04
BD	-3.9 ± 1.6	-2.6 ± 0.8
ΔT	0.27 ± 0.19	0.30 ± 0.16

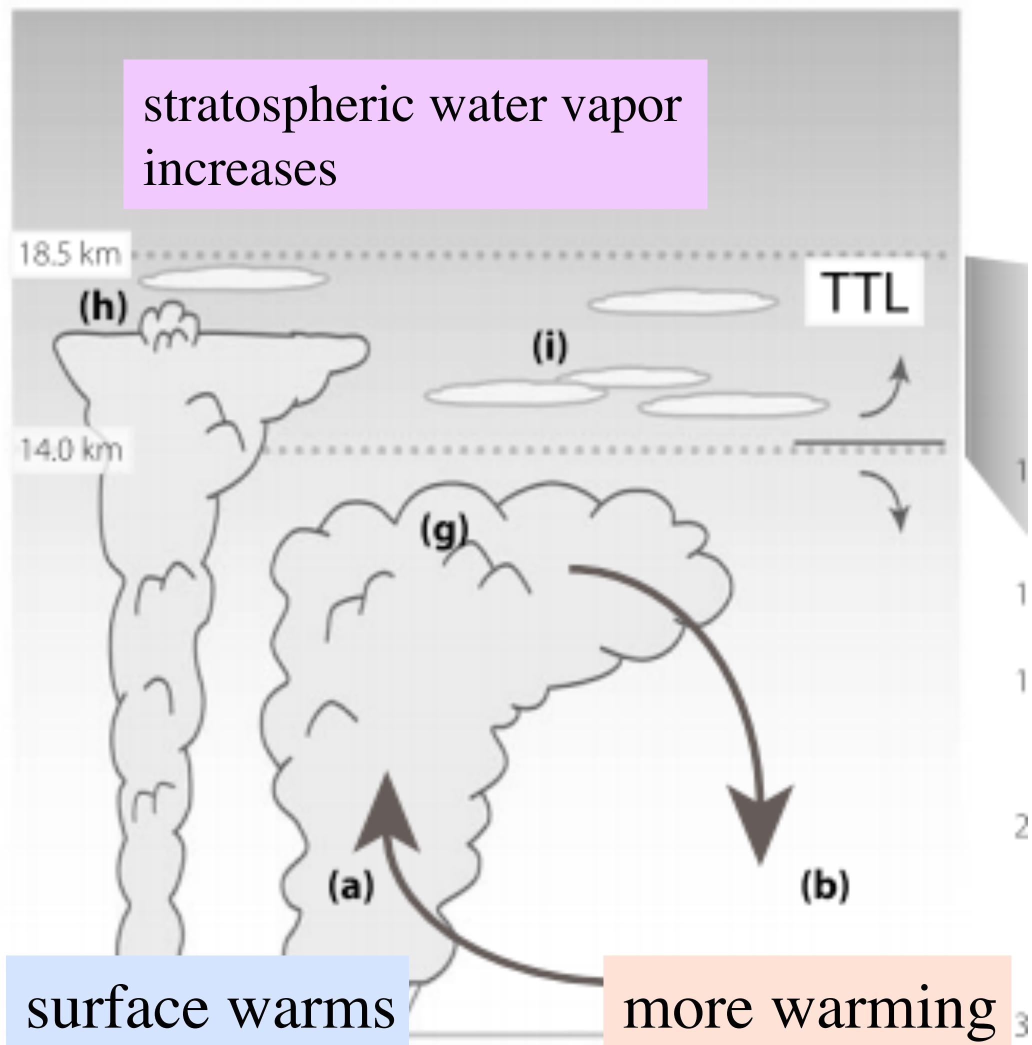
The units of the QBO, BD, and ΔT coefficients are ppm, ppm/(K/d), ppm/K, respectively. The uncertainty is the 95% confidence interval. The two MLS fits use MERRA and ERAi values of BD and ΔT.

$$H2O^* = a\ QBO + b\ BD + c\ \Delta T + r$$

Dessler et al., PNAS, 2013



Fueglistaler et al., 2009: The tropical tropopause layer, Rev. Geophys., 47, RG1004, doi: 10.1029/2008RG000267.



Fueglistaler et al., 2009: The tropical tropopause layer, Rev. Geophys., 47, RG1004, doi: 10.1029/2008RG000267.

TTL review

- understanding the annual and interannual variations in H_2O
- trends in H_2O?
- other constituents

GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 7, PAGES 1195-1198, APRIL 1, 2001

Stratospheric water vapor increases over the past half-century

K.H. Rosenlof[1], S.J. Oltmans[2], D. Kley[3], J.M. Russell III[4], E-W. Chiou[5], W.P. Chu[6], D.G. Johnson[7], K.K. Kelly[1], H.A. Michelsen[8], G.E. Nedoluha[9], E.E. Remsberg[6], G.C. Toon[10], M.P. McCormick[4]

Abstract. Ten data sets covering the period 1954-2000 are analyzed to show a 1%/yr increase in stratospheric water vapor. The trend has persisted for at least 45 years, hence is unlikely the result of a single event, but rather indicative of long-term climate change. A long-term change in the transport of water vapor into the stratosphere is the most probable cause.

Data Analysis

Fig. 1 shows CMDL and HALOE data at 21 hPa. This leve
above where the seasonal cycle impacts the analysis, thereby a
sampling biases. A regression analysis including linear, 27
quasi-biennial, annual, and semiannual terms for the period Ja
through Mar. 2000 yields a linear change (1σ uncertainty) of

GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 7, PAGES 1195-1198, APRIL 1, 2001

Stratospheric water vapor increases over the past half-century

K.H. Rosenlof[1], S.J. Oltmans[2], D. Kley[3], J.M. Russell III[4], E-W. Chiou[5], W.P. Chu[6], D.G. Johnson[7], K.K. Kelly[1], H.A. Michelsen[8], G.E. Nedoluha[9], E.E. Remsberg[6], G.C. Toon[10], M.P. McCormick[4]

Abstract. Ten data sets covering the period 1954-2000 are analyzed to show a 1%/yr increase in stratospheric water vapor. The trend has persisted for at least 45 years, hence is unlikely the result of a single event, but rather indicative of long-term climate change. A long-term change in the transport of water vapor into the stratosphere is the most probable cause.

Data Analysis

Fig. 1 shows CMDL and HALOE data at 21 hPa. This leve above where the seasonal cycle impacts the analysis, thereby a sampling biases. A regression analysis including linear, 27 quasi-biennial, annual, and semiannual terms for the period Ja through Mar. 2000 yields a linear change (1σ uncertainty) of

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Stratospheric water vapour changes as a possible contributor to observed stratospheric cooling

Piers M. de F. Forster and Keith P. Shine

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Abstract. The observed cooling of the lower stratosphere over the last two decades has been attributed, in previous studies, largely to a combination of stratospheric ozone loss and carbon dioxide increase, and as such it is meant to provide one of the best pieces of evidence for an anthropogenic cause to climate change. This study shows how increases in stratospheric water vapour, inferred from available observations, may be capable of causing as much of the observed cooling as ozone loss does; as the reasons for the stratospheric water vapour increase are neither fully understood nor well characterized, it shows that it remains uncertain whether the cooling of the lower stratosphere can yet be fully attributable to human influences. In addition, the changes in stratospheric water vapour may have contributed, since 1980, a radiative forcing which enhances that due to carbon dioxide alone by 40%.

variability needs to be taken into account. Hence the attribution of temperature change to ozone loss remains tentative.

This paper examines another possible contributor to cooling in the lower stratosphere, namely increases in stratospheric water vapour. It has been known for some time that increases in stratospheric water vapour can (a) cause a surface warming and (b) cause a stratospheric cooling (e.g. [*Rind and Lonergan*, 1995]). Between 1981 and 1994 increases in lower stratospheric water vapour of 30-60 ppbv/year have been observed below 30 km over Boulder, Colorado [*Oltmans and Hofmann*, 1995] from balloonsonde measurements which have been sustained to the present day (Oltmans and Hofmann, personal communication). Over the rest of the globe there is no such long term record. However, trends derived from the Halogen Occulation Experiment (HALOE) flying on the Upper Atmosphere Research

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Contributions of Stratospheric Water Vapor to Decadal Changes in the Rate of Global Warming

Susan Solomon,[1] Karen H. Rosenlof,[1] Robert W. Portmann,[1] John S. Daniel,[1] Sean M. Davis,[1,2] Todd J. Sanford,[1,2] Gian-Kasper Plattner[3]

Stratospheric water vapor concentrations decreased by about 10% after the year 2000. Here we show that this acted to slow the rate of increase in global surface temperature over 2000–2009 by about 25% compared to that which would have occurred due only to carbon dioxide and other greenhouse gases. More limited data suggest that stratospheric water vapor probably increased between 1980 and 2000, which would have enhanced the decadal rate of surface warming during the 1990s by about 30% as compared to estimates neglecting this change. These findings show that stratospheric water vapor is an important driver of decadal global surface climate change.

Occultation Experiment
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from late 1991 through
coverage extending from
stratopause over 65°S to
shows the time series of n
in the lower stratosphere
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data from the Stratospher
periment II (SAGE II) (1
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Taken together, these da
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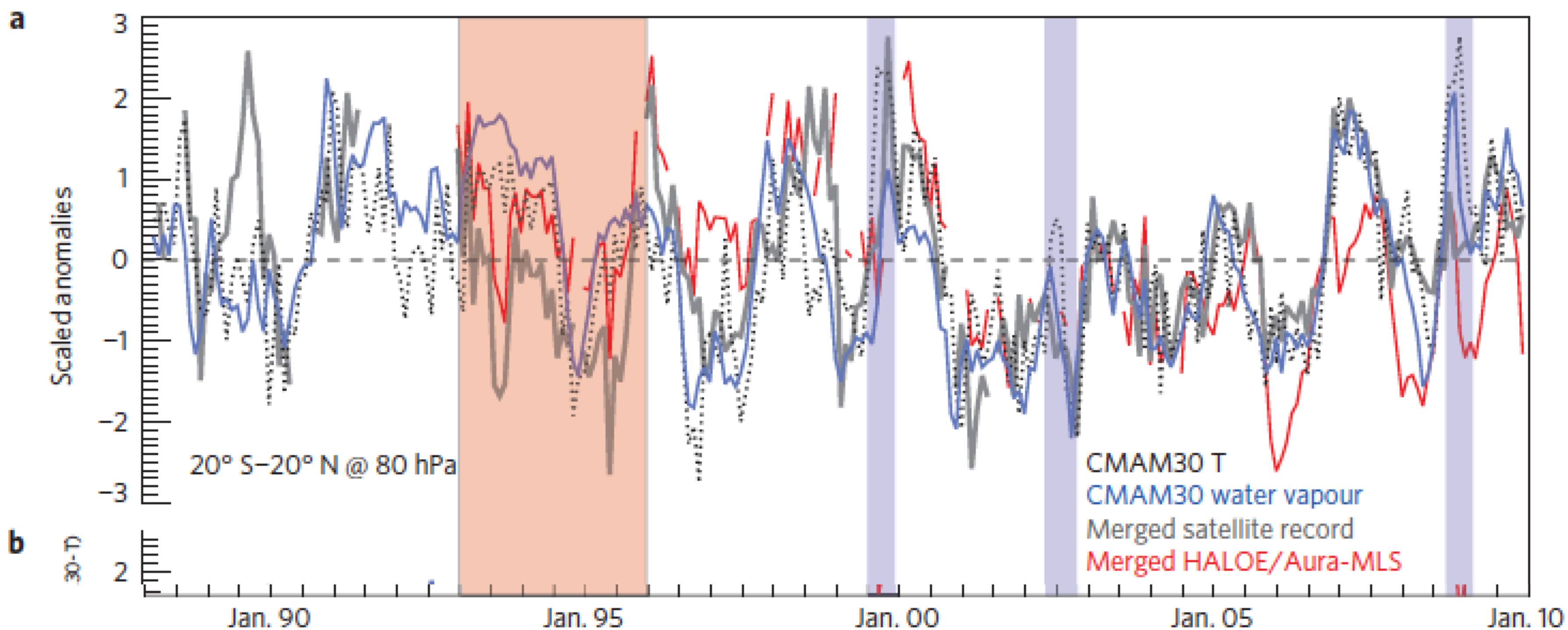
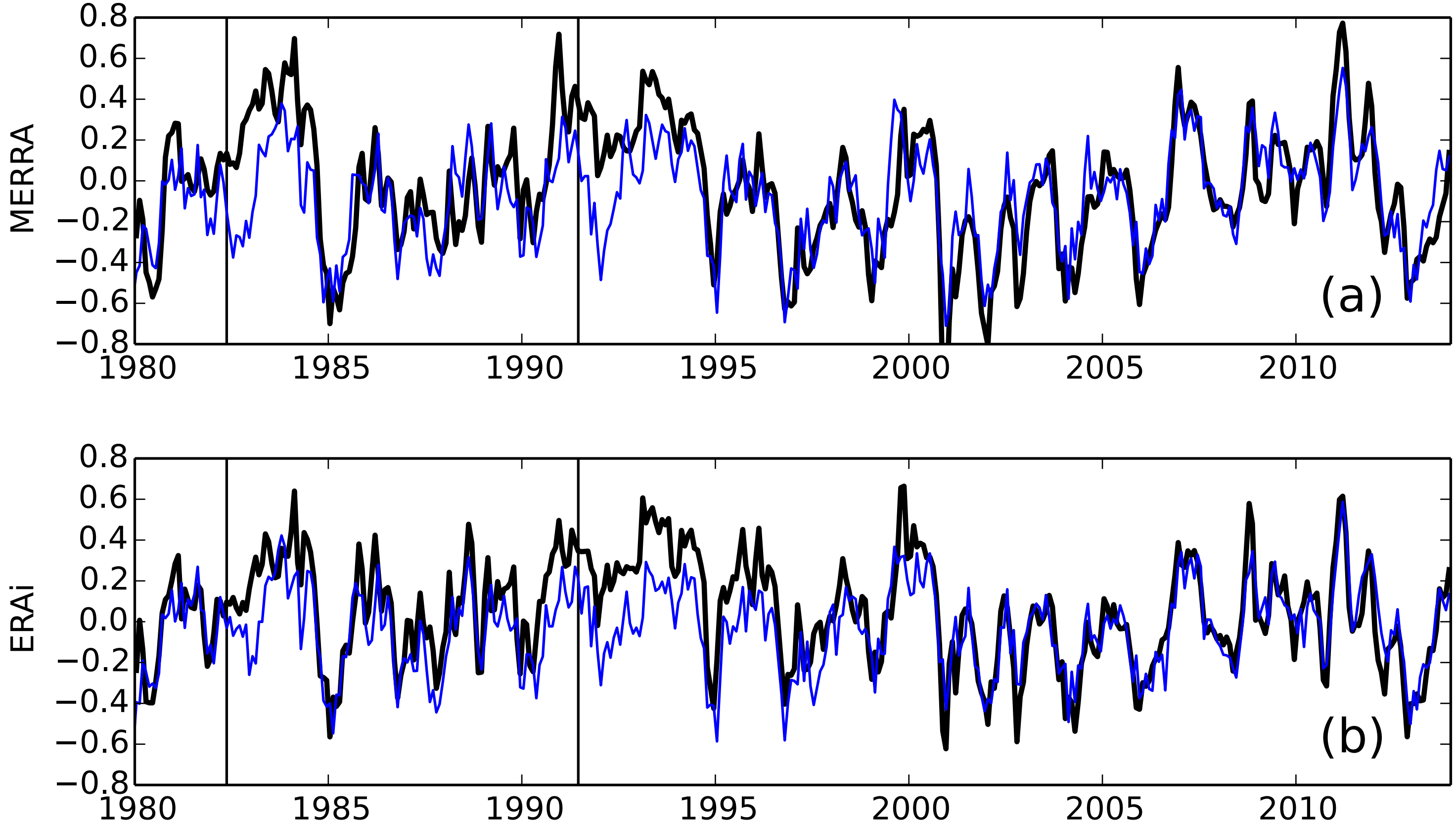
0.4 parts per million by v
year 2000. Observations
tropical ozone changes als
after 2000 (*15*). Before th
data suggest a gradual r
lower-stratospheric wate
1 ppmv from about 1980

Trends in strat. H_2O

- increase in H_2O entering the stratosphere
- increase in CH_4 entering the stratosphere
- increase in fraction of CH_4 oxidized in stratosphere



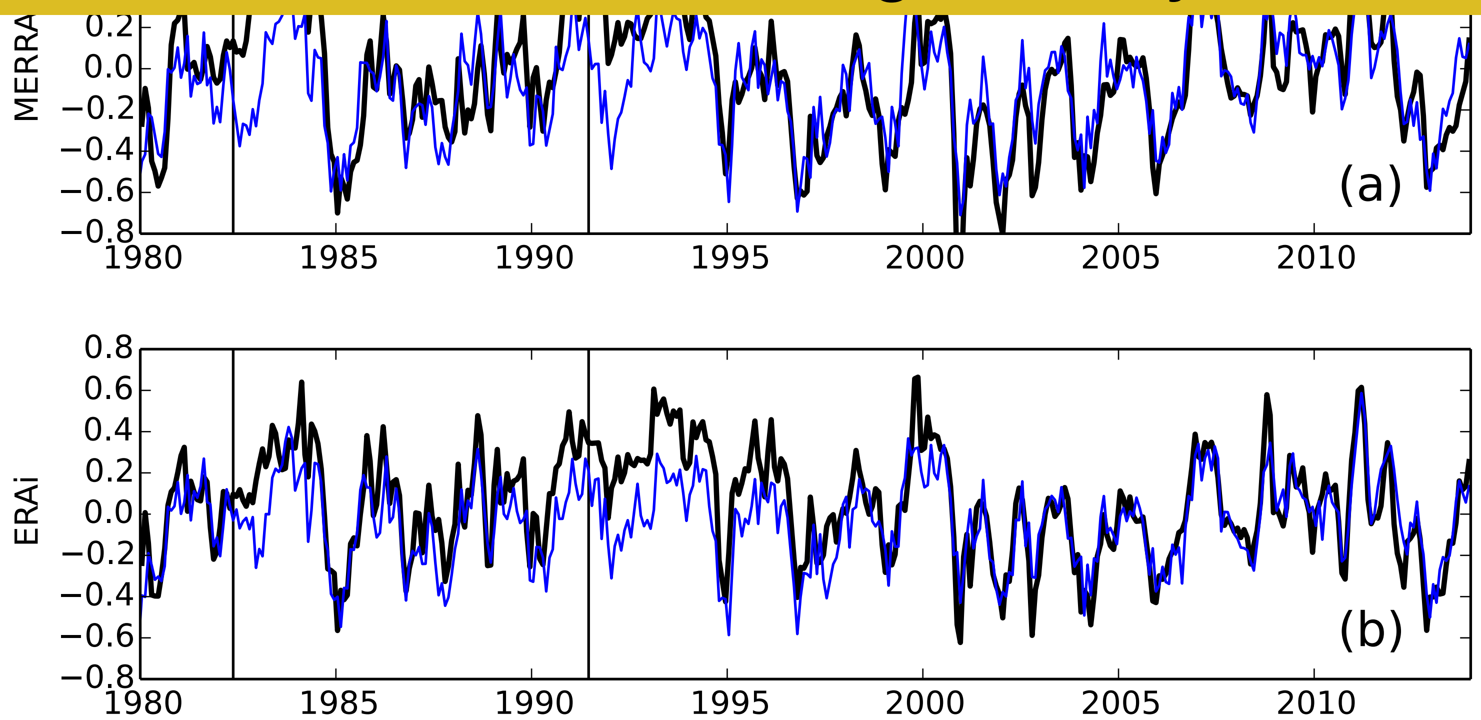
Hegglin et al., Nat. Geosci., 2014



No evidence of trend in H_2O through the TTL

Strongly subject to endpoint effects

This casts doubt on the idea that stratospheric water has been increasing at 1%/year



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TTL review

- understanding the annual and interannual variations in H_2O
- trends in H_2O?
- other constituents

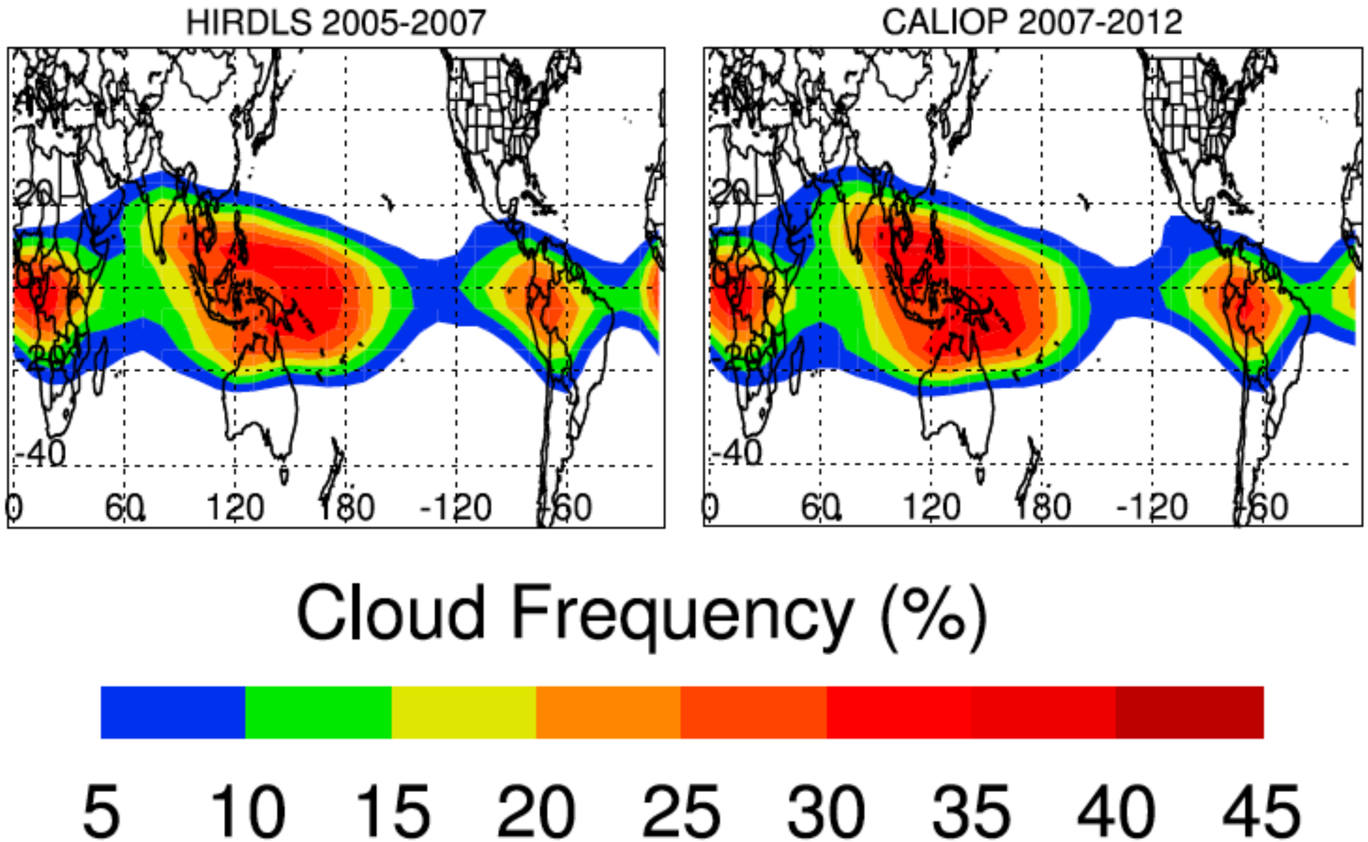
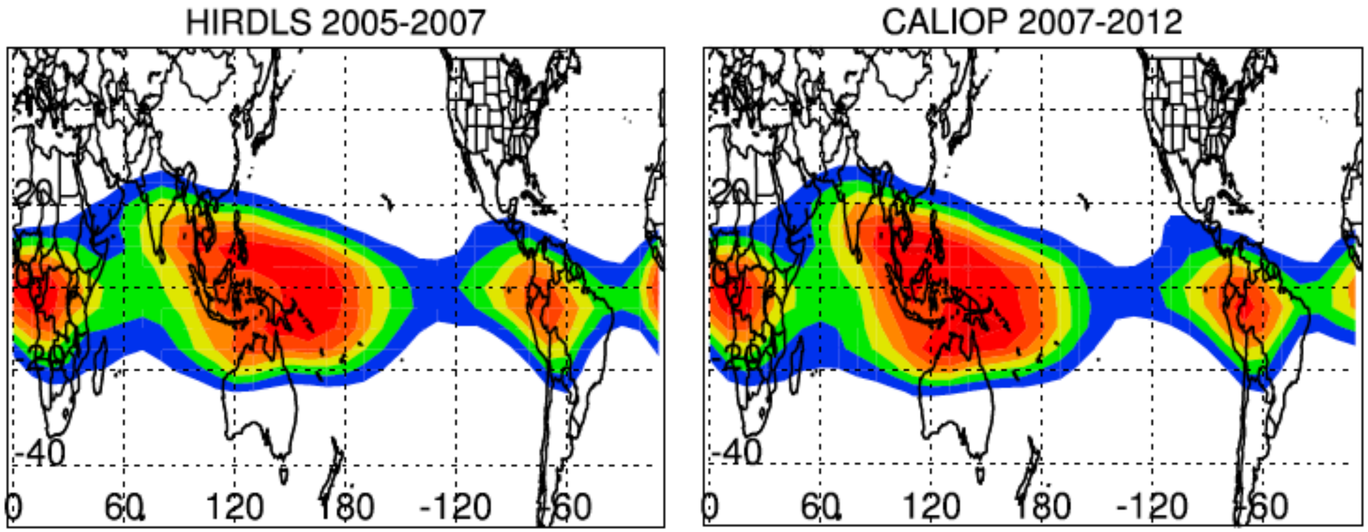
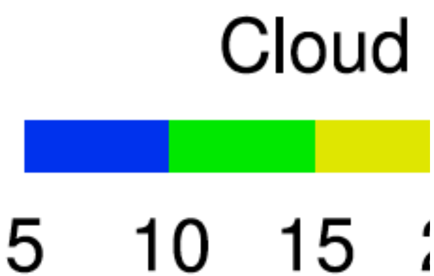


Figure 3. Average cloud frequency of occurrence centered at 100 hPa based upon SAGE, HALOE, and HIRDLS extinction data at vertical resolutions near 1 km and CALIOP CLay cloud layer data for the 16.2–17.2 km altitude range. The years of the averaging are indicated in each panel.

Massie et al., JGR, 2013





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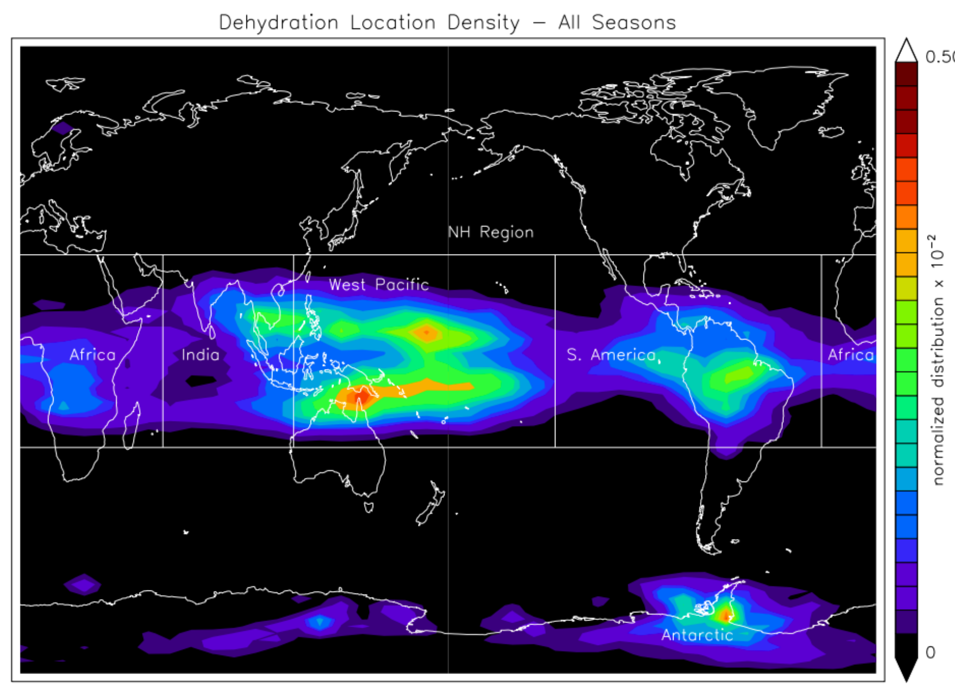
HIRDLS extinction data at vertical resolut
17.2 km altitude range. The years of the a

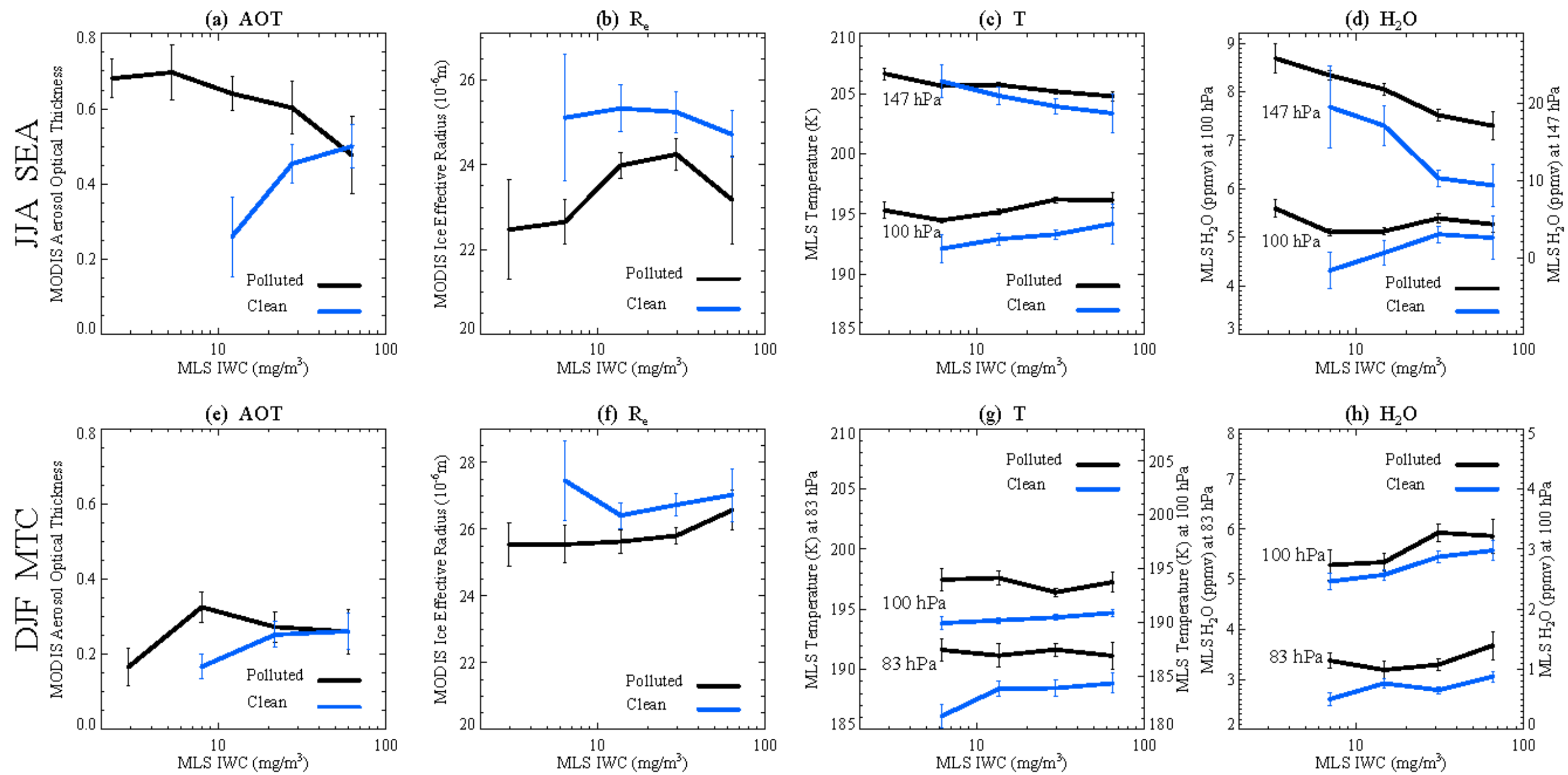
Massie et al., JGR, 2

(a)



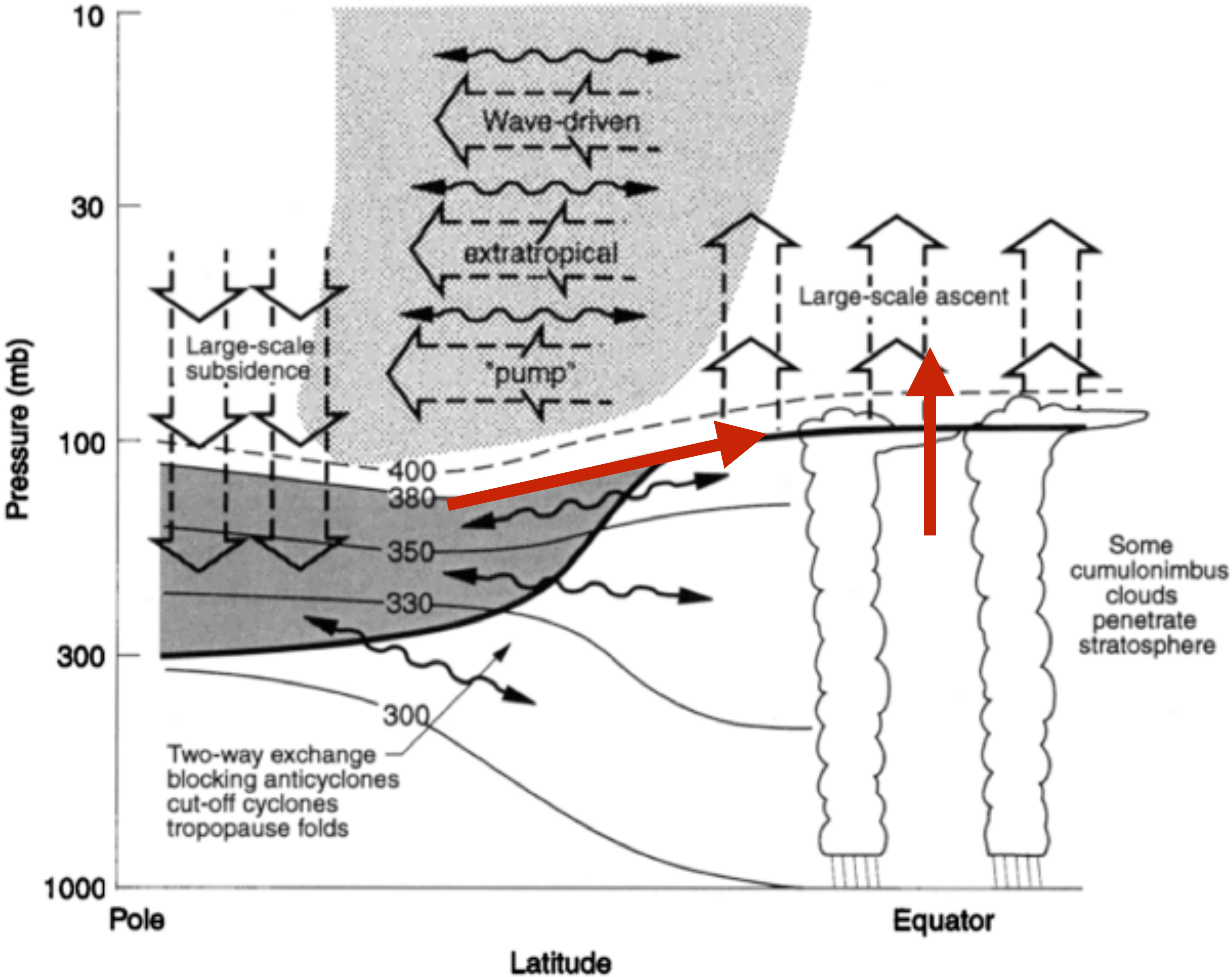
Schoeberl and Dessler, ACP, 2011

Aerosol-Clouds-Water Vapor Interactions



Using Aura MLS and MODIS data, Su et al. (2011) found that polluted ice clouds over Asia have smaller effective radius (R_e), higher temperature (T) and water vapor (H_2O) than clean clouds in the tropical tropopause layer (TTL), indicating a warming and moistening effect on air entering the stratosphere by the pollutants in Asia. Thus, the increasing aerosols in Asia may have significant impact on stratospheric water vapor, ozone chemistry and global radiative balance.

Su, H., J. H. Jiang, et. al., Observed increase of TTL temperature and water vapor in polluted clouds over Asia, *J. Climate,* 24, 2728-2736, 2011.

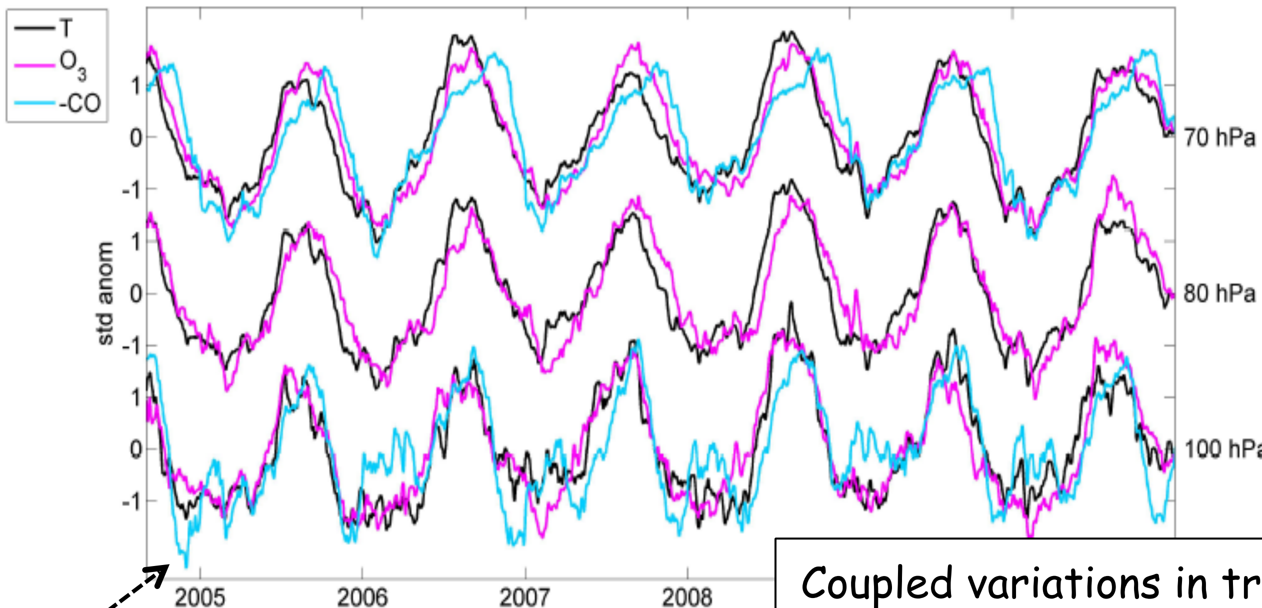

10
30
100
300
1000
Pressure (mb)
Wave-driven
extratropical
"pump"
Large-scale subsidence
Large-scale ascent
400
380
350
330
300
Some cumulonimbus clouds penetrate stratosphere
Two-way exchange
blocking anticyclones
cut-off cyclones
tropopause folds
Pole
Equator
Latitude

Variability in upwelling across the tropical tropopause and correlations with tracers in the lower stratosphere

ACP, 2012

M. Abalos[1], W. J. Randel[2], and E. Serrano[1]

Temperature, ozone and CO in the tropical lower stratosphere



CO inverted scale

Coupled variations in tracers reflects influence of tropical upwelling

Wang, T., W. J. Randel, A. E. Dessler, M. R. Schoeberl, and D. E. Kinnison (2014), Trajectory model simulations of ozone (O3) and carbon monoxide (CO) in the lower stratosphere, Atmos. Chem. Phys., 14, 7135-7147, doi: 10.5194/acp-14-7135-2014.

Conclusions

- Aura's measurements have improved our understanding of the TTL
- We have an improved understanding of H2O regulation
- Long-term 1%/yr increase is increasingly doubtful
- Other constituents play a key role in understanding TTL dynamics
- Lots of things I didn't talk about